THE VARIABILITY OF FLY ASH AND ITS EFFECTS ON SELECTED PROPERTIES OF FRESH PORTLAND CEMENT/FLY ASH MORTARS

A Thesis

by

WILLIAM CARLTON MCKERALL

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Approved as to style and content by:

(Chairman of Committee)

(Member)

(Member)

(Head of Department)

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ABSTRACT

The Variability of Fly Ash and Its Effects on Selected Properties of Fresh Portland Cement/Fly Ash Mortars. (December, 1980)

William Carlton McKerall, B.S., Texas A&M University

Chairman of Advisory Committee: Dr. W. B. Ledbetter

This thesis evaluates fly ashes, from five power plants in Texas, as mineral admixtures to partially replace portland cement in portland cement concrete. The variability and compliance with specifications were determined for each of the five ashes. Furthermore, expedient evaluation procedures were developed enabling rapid determination of certain critical ash properties and the variability of those properties.

The chemical and physical properties were analyzed for the degree of correlation that existed between them. The initial set, final set, entrained air content, and flow were measured for mortar mixtures with water-cement ratios of 0.4, 0.5, and 0.6 and cement replacements of 10, 20, and 30 percent fly ash. The effects of the chemical and physical variabilities from the five fly ashes were then determined on the above behavioral characteristics.

Some of the major conclusions reached were:

1. Fly ash exhibits a quite variable nature, yet not to the extent that might be expected from a waste product.

2. The CaO content can be consistently determined from the CaO heat evolution test, and the percent retained on a No. 325 sieve and

specific gravity can be accurately estimated from both the heat evolution test and No. 200 sieve analysis.

3. A very strong correlation is indicated between CaO, SiO_2, specific gravity, fineness, LOI, MgO, SO_3, and Na_2O alkali equivalent. Higher quantities of MgO, SO_3, LOI, CaO, and Na_2O equivalent are seen together with larger specific gravities and lower values of SiO_2 and percent retained on a No. 325 sieve.

4. The inclusion of fly ash in cement mortars almost invariably retards the time of set dependent on the concentrations of Al_2O_3, Fe_2O_3, and SiO_2. The aluminate and ferrite compounds appeared to retard initial and final set times, while SiO_2 accelerated the final set.

5. Increasing replacements of cement with fly ash consistently increased the flow even though larger volumes of fly ash were used in place of the cement. This is probably because fly ash particles are spherical in shape versus the more angular cement particles. High SiO_2, lower CaO, and reduced specific gravity appear to be associated with increased flow.

6. The fluctuation of air content was found to be strongly correlated with the fineness and LOI of a fly ash. Higher finenesses and LOI values appeared to reduce the amount of entrained air.

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Special thanks are due to two special people, Sabrina Hardin and Marjorie McKerall for the typing of preliminary and rough drafts. The typing of the final copy by Mrs. Bea Cullen is also greatly appreciated.

Finally, the author acknowledges his Lord, Jesus Christ as being the true source of strength behind the completion of this work. It was for His glory that this past year was undertaken, and therefore, it is to Him and the glory of God that this thesis is now dedicated.

> Whatever you do, do your work heartily for the Lord, rather than men, knowing that from Him you will receive the reward of the inheritance; it is the Lord Christ whom you serve. --Paul--
>
> Colossians 3:23-24

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CHAPTER 1

INTRODUCTION

The Problem

Rising construction costs in recent years have become a growing source of concern for the construction industry and the United States as a whole. This inflationary trend combined with complicated structural designs that are more demanding on building materials has created the need for development of more economical, yet structurally sound construction methods and materials.

Portland cement concrete currently stands, by far, as the most utilized construction material in the world. In fact, the amount of concrete used today exceeds that of all other construction materials combined. Nonetheless, this workhorse of the construction industry is a major contributor to building cost increases. In 1979 alone, 700 million tons of concrete were placed in the United States,so it is clear what the implications of strong cost control with concrete can be. The potential savings to be reaped, even with small reductions in unit price, are quite significant (1).

The ingredient responsible for the large part of concrete cost increases is the most crucial component, portland cement. The production of portland cement has and will continue to be an energy

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This thesis follows the style and format of the Transportation Research Board's Transportation Research Record.

intensive industry with approximately 15 percent of production costs being expended to procure energy. It requires 2200 kilowatt-hours to produce one ton of cement, and as energy costs continue to rise, the price of cement and subsequently concrete will also increase (2).

Efforts to curb the spiraling cost of concrete have been channeled in several directions, most related to decreasing cement cost. From the first hints of the energy crunch, cement producers have involved themselves in very successful energy conservation programs. Plant designs and production technology are continuously being reworked to extract the highest amount of cement per kilowatt-hour. Lightweight concrete has again emerged as economical by decreasing the amount of costly concrete and cement to be used. Super-plasticizing admixtures have also been developed which increase concrete strengths and reduce concrete and cement contents.

A separate approach has been the development of less expensive materials to partially replace the portland cement in concrete. Along these lines, fly ash, a by-product of coal combustion,has been shown to be a promising possibility. The inclusion of fly ash in portland cement concrete has generally been found to improve the properties of both fresh and hardened concrete at reduced costs. Fly ash, however, is not universally accepted as an ingredient in concrete. Significant discrepancies exist surrounding the effects of fly ash on certain key properties of concrete. Some experts suggest that as high as 35 percent of the fly ash produced in America is unsuitable for use in concrete, yet to date, there have been no failures of fly ash concrete attributable to fly ash quality.

The foremost problem associated with fly ash has been the reluctance to use a waste product as a replacement of portland cement in structural concrete (3, 4). Only recently has the industry recognized the possibility of accepting fly ash as a permissible ingredient in most concrete. This difficulty can be further mediated by continued research and transfer of knowledge to industry.

A second problem, which is related to the first, is variability. The performance of a highly variable ash in concrete is uncertain at best, often rendering its use impractical. It is therefore necessary to thoroughly understand the variability of ash from each individual source in order to provide the needed quality control of concrete.

Another source of concern results from the recent development of lignite and sub-bituminous coal as fuel sources. The ash produced from these coals is of a different chemical composition than traditional bituminous fly ashes. The use of these newer coal ashes in concrete is technically different, and while feasible, it is in a more developmental stage. Additional research must be undertaken to discern the characteristics of sub-bituminous and lignite fly ashes in concrete.

Objective

The objectives of this research were to analyze the variability of sub-bituminous and lignite fly ashes and to determine the effects that selected properties of these ashes have on certain characteristics of portland cement/fly ash mortars.

Scope

This study dealt with five sub-bituminous and lignite fly ashes from throughout Texas. The investigation included:

1. Gathering data on the properties of individual ashes and fly ash/portland cement mortars.

2. Developing tests to rapidly determine fly ash uniformity.

3. Determining the variation of chemical, physical, and performance characteristics.

4. Examining the possible interrelationships of physical, chemical, and selected performance properties of fresh fly ash/portland cement concrete mortars.

5. Summarizing the results, conclusions, and recommendations into a concise report.

In examining the variability, a set of four tests were performed on 342 fly ash samples. In addition, 44 samples underwent a complete chemical analysis. Finally, the effects of fly ash on the following fresh properties were examined:

1. Air content
2. Water requirement
3. Pozzolanic activity index
4. Flow
5. Times of initial and final set.

Upon completion of all testing, an analysis of possible relationships was performed. Additional research on this topic, combined with the knowledge gained from this study, will ultimately provide the background for more widespread utilization of sub-bituminous and lignite fly ash in concrete.

CHAPTER 2

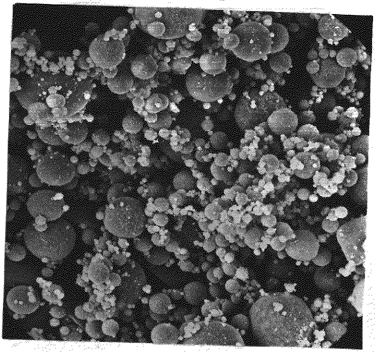
BACKGROUND

General

Fly ash is a by-product of pulverized coal combustion. It constitutes the very fine particulate matter which escapes the combustion chamber of coal fired electric generating plants. The ash is swept out of the boilers with the flue gases and then extracted by various mechanical and electrical means.

The primary building blocks of fly ash are microscopic, spherical granules composed chiefly of silica, alumina, iron, and calcium oxides (Figure 1). These granules are formed when small particles of clay, pyrite, and calcite from within the coal are exposed to the heat of the combustion chamber (5, 6, 7). While in the flame zone, the clay particles are transformed into glass-like spheres of complex aluminates and silicates, the pyrite particles form iron oxides, and the calcite becomes calcium oxide. This transformation takes place in a molten state, and the tiny droplets formed are a mixture of the compounds mentioned above with smaller amounts of other minor compounds intermingled. The residual fly ash is for the most part a heterogeneous mixture of highly vitreous, spherical particles, crystalline matter, and unburnt coal (5, 6, 7).

Fly ash is classified as a pozzolan, a siliceous/aluminous material which, in finely divided form and in the presence of moisture, will react with calcium hydroxide to form compounds



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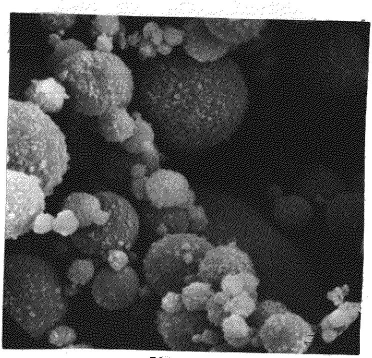

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Figure 1. Photomicrographs of fly ash from sub-bituminous coal.

possessing cementitious properties (8). In concrete, the pozzolanic action takes place when the silica and alumina from fly ash react chemically with the excess lime liberated during the hydration of portland cement. It is important to note here that some types of fly ash, in addition to being pozzolanic as mentioned above, possess sufficient amounts of calcium silicates to demonstrate cementitious properties similar to portland cement (3, 9).

Variability

The utility industry produces the majority of the nations fly ash, and the ash produced is highly variable in chemical and physical properties. No two fly ash sources produce identical ashes, and furthermore, the variance in fly ash produced by the same plant can be quite noticeable.

Variability is a crucial characteristic of any fly ash used in concrete. Significant variance in ash properties could alter performance or design aspects of the concrete to unacceptable levels. For this reason, there is a definite need to analyze the variability of chemical and physical properties from each individual ash source and subsequently determine the properties which influence the behavior of vital performance characteristics in concrete.

The factors which most influence individual ash properties are:

1. Coal source
2. Degree of coal pulverization
3. Boiler unit design

4. Loading and firing conditions
5. Ash collection and processing methods
6. Fly ash storage methods (5).

The above items are characteristics peculiar to each plant, and to varying degrees, they are factors in both the variability between plants and variability within a plant. By far, the most influential factor of the ash produced is coal source. Faber and Styron note that, "The variable composition of coal is distinctive as it relates to the composition of the resulting fly ash produced through combustion. It is these variations that have and will continue to be of concern to the fly ash industry" (9). The variability of the coal introduced for combustion determines to a very large extent the predictability of the collected fly ash. Ashes with high variability are of low value for use in concrete due to the unpredictable nature they impart to both fresh and hardened properties of the concrete.

Apart from the variance that exists within each plant, there is an overall broad range in ash composition depending on the character of the coal source. In nature, coal exists in varying grades or amounts of burnable material per unit weight. The most common grades of coal used for power generation are bituminous, sub-bituminous, and lignite. Table 1 provides a breakdown of these classifications based on their energy potential.

Bituminous coal, sometimes referred to as eastern coal, is predominantly found in eastern and north central states and is usually obtained by deep mining operations. It is characteristically higher in carbon content; therefore, both the energy potential and burning

Table 1. Grades of coal delivered to electric utilities, 1976 (1).

Coal Grade	Quantity (1000 ton)	% of Total	Average Btu/lb.	Range [a] Btu/lb.
Bituminous	364,227	80.1	11,407	>11000
Sub-bituminous	67,309	14.8	9,242	8300-13000
Lignite	22,211	4.9	6,509	< 8300

a These values obtained from ERDA, 1976, (10).

efficiency are higher with bituminous than sub-bituminous or lignite coals. Sub-bituminous and lignite coal are somewhat 'dirtier' coals reaped from strip mines in western and southwestern regions of the country; hence, their label as western coals. They possess substantially higher quantities of noncombustible mineral matter per unit weight and so yield larger amounts of ash.

The American Society for Testing and Materials (ASTM) divides fly ash into two distinct classes based on coal source--class F from bituminous coal and class C from sub-bituminous and lignite origins. It is along these lines, bituminous and sub-bituminous/lignite, that a contrast exists between the chemical compositions of the resulting ashes. To what extent these differences affect concrete has yet to be fully explored.

Table 2 lists the ranges in chemical composition for bituminous and lignite coal, determined by three separate sources. Note that bituminous ashes have comparatively lower CaO (lime) contents and higher amounts of silicate, aluminate, and ferrite than do their class C counterparts. It is for this reason that class F ashes are often termed 'low-lime', and class C 'high-lime'. It is the high-lime fly ashes from sub-bituminous and lignite sources that possess both the pozzolanic and hydration characteristics mentioned earlier. Figure 2 shows clearly the hydration reaction of a sub-bituminous fly ash exposed to water for seven days. The products of the reaction appear to be similar to those of a portland cement paste, which indicates that the presence of CaO is very influential.

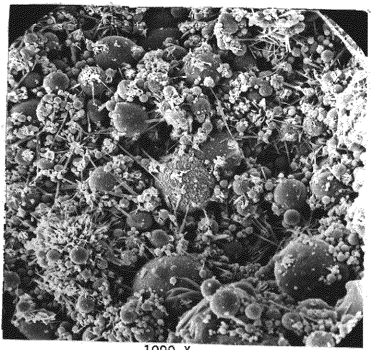
Table 2. Ranges in chemical composition of lignite and bituminous coal.

Coal Grade	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Alkalies	C
Bituminous								
A	34-52	13-31	6-25	1-12	0.5-3	0-2	0-2	1-12
B	25-52	14-30	4-31	3-8	0.5-3	0.3-3	0.5-9	1-19
C	40-55	25-35	5-24	0.5-4	0.5-5	0.5-5	0.7.4	0.5-12
Lignite								
A	15-52	8-25	2-9	11-36	2-11	0.7-27	0-7	1-12
B	24-43	12-21	5-14	18-41	4-10	0.7-2.5	0.5-5	1-4
C	20-40	10-30	3-10	10-32	0.5-8	1-8	1-8	0.5-2

A Price, et al. (1).

B Department of Energy (2).

C Faber and Styron (9).



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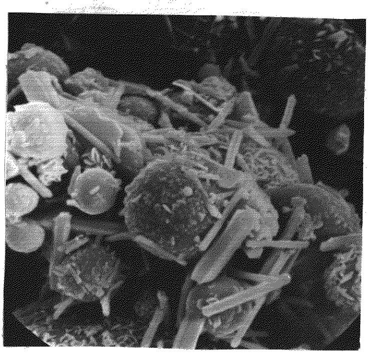

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Figure 2. Photomicrograph of fly ash from sub-bituminous coal exposed to moisture for seven days.

Specifications

ASTM recommends specifications for both class F and class C fly ashes (8). Tables 3 and 4 list these suggested chemical and physical requirements for ash used as a concrete admixture. By comparing Tables 2 and 3 it becomes apparent that the minor compounds in fly ash are of most concern, because they often occur in excess of recommended percentages. Class C ashes are particularly notorious for possessing high amounts of these lesser compounds.

Magnesium oxide (MgO), sulfur trioxide (SO_3), carbon (C), and various alkalies (Na_2O and K_2O) are all potential 'bad actors' in cement and must be limited to minimize their deleterious effects. MgO is a compound that hydrates similar to lime; however, its hydration occurs slower and can be accompanied by disruptive expansions (11, 12). SO_3 is often added to cement in the form of gypsum to slow the fast setting action of hydrating aluminates. The SO_3 and aluminate contents must be closely matched for the aluminate compounds to be properly retarded and the SO_3 largely expended. If relatively high concentrations of gypsum are present with respect to the aluminates, the residual SO_3 will form disruptive compounds in the hardened concrete. The presence of alkalies also has an effect upon setting times. High alkali contents reduce the retarding action of lime and can contribute to flash setting without adequate SO_3 levels. Alkalies from within fly ash also have the potential to react with certain siliceous aggregates which cause disruptive expansions in hardened concrete. Fly ash can be used as a silica flour to mitigate such alkali-aggregate reactions; however, if high quantities of alkali are present in the fly

Table 3. ASTM C-618 chemical requirements (8).

Criteria	Mineral Admixture Class	
	F	C
$SiO_2 + Al_2O_3 + Fe_2O_3$ (min %)	70.0	50.0
SO_3 (max %)	5.0	5.0
Moisture Content (max %)	3.0	3.0
Loss on Ignition (max %)	12.0	6.0
MgO (max %)**	5.0	5.0
Available Alkalies as Na_2O (max %)**	1.5	1.5

** Optional

Table 4. ASTM C-618 physical requirements (8).

Criteria	Mineral Admixture Class F	Mineral Admixture Class C
<u>Fineness</u>		
No. 325 sieve (max % retained)	34	34
<u>Pozzolanic Activity Index</u>		
28 day with portland cement (min % of control)	75	75
7 days with lime (min psi)	800	800
Water requirement (max % of control)	105	105
<u>Soundness</u>		
Autoclave expansion/contraction (max %)	0.8	0.8
<u>Uniformity Requirements</u>		
The specific gravity and fineness of individual samples shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than:		
Specific gravity, maximum variation average percent	5.0	5.0
Percent retained on No. 325 sieve, maximum variation, percentage points from average	5.0	5.0
Multiple factor, (the product of loss on ignition, amount retained on No. 325 sieve)	255	---
Increase of drying shrinkage of mortar bars at 28 days, maximum percent **	0.03	0.03

**Optional

Table 4. Continued.

Criteria	Mineral Admixture Class F	Mineral Admixture Class C
<u>Uniformity Requirements (con'd)</u>		
In addition, when air-entraining concrete is specified, the quantity of air-entraining agent required to produce an air content of 18.0 volume percent of mortar shall not vary from the average established by the ten preceding tests or by all preceding tests if less than ten, by more than, percent **	20	20
<u>Reactivity with cement alkalies</u>		
Mortar expansion at 14 days, maximum percent **	0.020	0.020

** Optional

ash itself, the mitigating effect can be essentially nullified. The concentration of these compounds in the fly ash used, combined with the amounts already present in the cement, will determine to what extent the finished concrete is affected (11, 12).

Unburned carbon particles, indicated by loss of ignition (LOI), are usually not found in portland cement, but can occur in large quantities within fly ash. These particles contribute nothing to the hardened concrete structurally, and have been shown to demonstrate an affinity for air entraining agent (AEA). The effect of this AEA absorption on freeze-thaw durability has been questioned and will be discussed in a subsequent section.

Two physical properties of fly ash that draw considerable attention are fineness and specific gravity. Fineness is controlled primarily by the efficiency of the coal pulverizers. In general, finer ashes react quicker to produce slightly higher early strengths and slightly faster set times. These finer ashes are also preferable because they tend to reduce the amount of water necessary for a given consistency (water requirement). Additional research is needed to isolate the properties of fly ash which influence the water requirement.

Some controversy exists over the significance of the specific gravity of fly ash. Several researchers have concluded this property to be of little practical use, while others claim strong correlations between specific gravity, fineness, and loss on ignition (13, 14). The specific gravity is relevant to mix designs because variations significantly alter the volume proportions of a mix.

Note also that ASTM recommends controlling the variability of fineness and specific gravity to provide tighter control of product uniformity. A deficiency in specifications that appears to exist is the absence of a CaO uniformity requirement in light of the activity associated earlier with this compound (Figure 2). The lack of such a specification probably stems from the difficulty in quickly determining CaO presence; nevertheless, the need for such a specification remains.

The pozzolanic activity index (PAI) and soundness are performance related specifications which indicate how the ash will actually behave in concrete. Determination of an ash's PAI is especially significant because it appraises the individual ash's strength development potential in concrete. The PAI ranges from below 50 percent to greater than 200 percent of a control test. An exhaustive literature review has revealed negligible information concerning the PAI of subbituminous and lignite ashes. Research is greatly needed to determine the ash properties responsible for good pozzolanic activity.

Bituminous Fly Ash

Bituminous coal burning power plants became prominent in eastern states around the turn of the century. A large concentration of these plants have evolved in that area with a correspondingly high fly ash production. Researchers have subsequently had the opportunity to develop a full body of knowledge concerning bituminous ash and its applications.

The first significant use of bituminous fly ash probably occurred in the 1940's when the Bureau of Reclamation started specifying large quantities of this ash to be placed in mass concrete to reduce the hydration heat. Because the pozzolanic activity occurs at a slower rate than cement hydration, the heat produced is dissipated over a longer period of time. In addition, the reduction in heat generation is largely responsible for the lower amounts of thermal cracking found in fly ash concrete.

The slower nature of the pozzolanic activity also delays the initial and final sets, and ultimately lowers the rate of early strength gain when compared to a 100 percent portland cement concrete. However, the set times usually remain within specifications, and it is quite common for the sustained strength gaining characteristics of fly ash concrete to produce higher strengths than comparable portland cement mixes at approximately 180 days (Figure 3)(15). Because of this phenomenon, fly ash has often been specified for high strength concrete. During construction of the Water Tower Place in Chicago, the world's tallest reinforced concrete building, high strength fly ash concrete was specified, and the Material Service Corps noted that the high strengths obtained were impossible without the addition of fly ash (16).

Several advantages of bituminous fly ash concrete are seen while the material is still plastic. The spherical particles of bituminous ash serve as miniature ballbearings that lubricate a mix. Better workability, placeability, finishability, and pumpability all result from this phenomenon. The same lubricating effect often makes it possible to increase coarse aggregate contents and reduce water

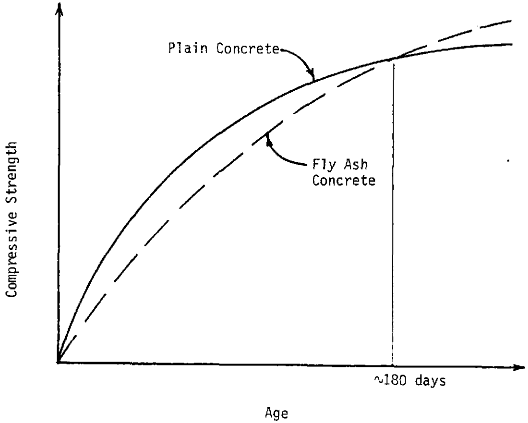

Figure 3. Comparison of strength development of concrete with and without fly ash.

contents for fly ash mixes of equal slump. Larger amounts of coarse aggregate raise the cementing efficiency while reduction in water lowers water-cement ratios causing strength to increase.

Two interrelated benefits of fly ash concrete are decreased permeability and leaching. The pozzolanic activity previously mentioned is a reaction between the silica and alumina particles of the fly ash and the lime that is freed by cement hydration. This reaction combines the potentially leachable lime into insoluble calcium silicates and aluminates that are quite stable. The silicates and aluminates formed actually solidify the concrete, filling voids and reducing the flow of the water in and out (17). The results of this occurrence are improved resistance to chemical attack and, according to some researchers, reduced freeze-thaw damage (13).

Some controversy exists surrounding the effects of fly ash on concrete subject to freezing and thawing. Early research indicated that bituminous fly ash reduced freeze-thaw resistance; however, these efforts often failed to account for the slower strength gains and higher sensitivity to air entrainment found in fly ash concrete. Research sponsored by the Department of Energy has shown that fly ash mixes of equal strength and entrained air content demonstrate freeze-thaw performance comparable to portland cement concrete (2).

Other advantages of bituminous fly ash concrete are (13):

1. Reduced segregation and bleeding
2. Reduced drying shrinkage
3. Improved molding and forming qualities

4. Reduced alkali reactions
5. Reduced cost.

Some of the disadvantages observed with fly ash concrete have been mentioned already. Low early strengths result from the slow strength gaining characteristics of the pozzolanic reaction. Researchers have also found that carbon from fly ash absorbs air entraining agent. This occurrence can adversely affect the air void system and subsequent freeze-thaw durability, especially when high carbon contents or highly variable carbon amounts exist in a given fly ash rendering control of AEA content impossible (13, 18). Other compounds such as SO_3, MgO, and Na_2O can also occur in bituminous fly ash to the extent that deleterious reactions occur. And finally, the initial expense incurred to provide a batch plant with fly ash handling capability is also a definite drawback (4).

Sub-Bituminous and Lignite Fly Ash

Bituminous, sub-bituminous, and lignite fly ashes are quite similar materials, yet variations in their chemical compositions make them technically distinct. The general consensus has been that certain performance characteristics of class C fly ash concrete were less than desirable; however, those premises have been largely abandoned in light of successful experience. To date there have been only small amounts of research with western ashes. Indeed, the vast majority of literature published concerning coal ash utilization has dealt almost exclusively with eastern, low-lime ashes. Only recently have class C ashes gained acceptance as cement replacements, and the need for their study been emphasized.

The surge in sub-bituminous and lignite fly ash utilization was initiated by the cement shortage of 1974. Many ready mix plants in western and southwestern states turned to the available quantities of fly ash as an extender. The plants were so pleased with the results that they continued using fly ash after the supply of cement was replenished. Conversion to western fly ashes has continued to increase as the rising cost of energy has rapidly inflated cement prices. The economic advantages combined with proven performance are major contributors to the growing acceptance of western ashes by industry.

Many of the same modifications imparted to concrete properties by class F ash are found in class C fly ash concrete; however, due to the slightly different compositions, some variations can be expected. Perhaps the most noticeable characteristic of western fly ash is the extreme range of compositions that may be encountered. By referring back to Table 2 (page 12), it can be seen that class C ashes cover a broader spectrum of chemical make-ups. There are even drastic differences in the ranges of composition reported by the three sources which, to some extent, indicates the newness and lack of research that exists. Major emphasis in the area of fly ash research is necessary to analyze the variability of sub-bituminous and lignite ashes and to relate ash properties and variability to the behavior of concrete.

Special attention should be directed towards the CaO content. The significance of this chemical property has already been established, and Table 2 (page 12) illustrates the broad variability of CaO quantities observed within lignite fly ashes. It appears that development of convenient CaO testing methods would greatly enhance the evaluation of sub-bituminous and lignite ashes.

Table 2 (page 12) also brings to light the high concentrations of MgO, SO_3, and alkalies possible in class C ashes. The effects of these potentially deleterious compounds have not yet been fully determined.

In general, the benefits obtained from class C ash are nearly identical to class F ash. Gifford Hill and Company, Inc., a marketer of class C fly ash and blended cements, has noted that, "Fly ash is a must in high strength concrete" (19). In addition, a North Dakota study has found that a 15 percent weight replacement of portland cement with lignite fly ash yields compressive strength results similar to 100 percent portland cement concrete (19). The study went on to conclude that the resistance to de-icer scaling and freeze-thaw durability was excellent. Strong correlations were indicated between alkali content and fineness, and the PAI was observed to be a poor indicator of compressive strength potential. Further research was urged pursuant to the last two findings mentioned.

Other generally recognized improvements to concrete facilitated by sub-bituminous and lignite fly ashes are (4, 20):

1. Improved workability, placeability, pumpability, and finishability
2. Reduced water requirement
3. Reduced heat of hydration and thermal cracking

4. Reduced drying shrinkage
5. Reduced bleeding and segregation
6. Reduced permeability and leaching.

Set time retardation and low early strengths have also been found to be characteristic of some western ashes. These properties are analogous to those observed with bituminous ash; however, some degree of uncertainty still surrounds the behavior of individual class C ashes. It would be highly beneficial for research efforts to focus on determination of the ash properties which control such things as time of set, PAI, air content, and other performance related characteristics of concrete.

A final benefit of western ash is its economic impact. In the recent construction of the El Paso Tower in Houston, Texas, fly ash was used as a partial cement replacement for the 7500 psi concrete. Not only did the concrete achieve strengths upwards of 8700 psi, but a quarter of a million dollars was saved due to the utilization of fly ash (4).

Other Factors

The advantages of fly ash utilization in concrete extend beyond the factors directly associated with concrete. Coal ash is a waste product produced in large quantities (48 million tons in 1978) (21). Disposal of this waste has and will continue to be an environmental, engineering and economic problem.

Recently, the Environmental Protection Agency (EPA) has become *interested in fly ash with respect of the National Resource Con*servation and Recovery Act (NRCRA). Basically, this act mandates the use of waste materials in government sponsored jobs where (22):

1. *The product is technically equivalent*
2. The product price is reasonable
3. Competition is maintained
4. The product is available.

Fly ash fits these criteria extremely well, so well in fact, that the EPA has taken a special interest in fly ash as a possible model for implementation of the NRCRA. The implications of this attention will be increased pressure for ash utilization.

Another factor mentioned briefly in Chapter 1 is that fly ash concrete saves energy. Several studies have examined the potential for energy conservation through the use of fly ash, and have reached the conclusion that huge quantities of energy could be conserved if ash were utilized. These studies point out that fly ash concrete is an accepted, if not necessary, construction material throughout the rest of the world. Twenty percent of the cement in South Africa and Japan contains fly ash, 25 percent in Germany, 33 percent in Russia, 60 percent in France and the Netherlands, and every pound of cement in Hungary is blended with fly ash. American production is less then 2 percent (1, 2). If the United States would convert just 25 percent of their annual cement production to a 20 percent fly ash blended cement, the equivalent of over 5.1 million barrels of oil would be conserved in energy every year (1).

In summation, engineering, environmental, energy, and economic pressures are all playing a role in the quickening development of this material. With these forces at work, it is becoming increasingly vital for research to keep pace and provide the knowledge necessary to insure efficient utilization.

CHAPTER 3

EXPERIMENTAL PROCEDURES AND RESULTS

Raw Materials

The fly ash used in this study originated from five power plants located in Texas. For the purpose of this thesis the five plants are denoted by the letters D, H, M, W, and B. Three of the plants supplied sub-bituminous fly ash and two plants furnished lignite fly ash. Samples were collected directly from each of the plants, and additional samples were obtained from construction sites where the ash was being utilized. The samples supplied by the power plants were collected at random over several days and at various operating conditions. Likewise, the ash obtained from the construction sites was also randomly sampled from delivery trucks. The random nature of the sampling was necessary to provide the clearest possible insight into actual plant variability.

The cement used in testing was a Texas produced, Type I portland cement in compliance with ASTM C-150, "Standard Specification for Portland Cement" (23). An air entraining agent was added to the mixing water prior to batching. The admixture was a saponified wood resin conforming to ASTM C-260, "Standard Specification for Air Entraining Admixtures for Concrete" (8). The two sands used in the mortars were silica sands supplied by the Ottawa Silica Company. The sand used for testing the Water Requirement and Pozzolanic Activity Index conformed to the specifications of ASTM C-109 (23). The sand used for all other testing complied with ASTM D-1556 (24). Data on all these materials are given in Appendix A.

The water used for making samples was ordinary tap water which was collected and allowed to become temperature stabilized before use. The water temperature was a constant 75.8° ± 1.7°F for the duration of the testing. The air temperature in the vicinity of testing remained in a range from 73.2°F to 77.9°F.

Testing Procedures and Results

The experimental design and testing can be broken down into three basic sections. One series of tests was designed specifically for variability study; a second program was aimed at determining the chemical compositions encountered; and a third test sequence focused on performance aspects of fly ash in fresh mortars.

Variability Testing

The initial test series involved performing four tests on each of the 342 fly ash samples collected. The emphasis of this series was the development of quick tests for field determination of fly ash acceptability with regards to variance. The variability of the five ashes was also analyzed with this test series. The four tests performed were:

1. Percent retained on the No. 325 sieve
2. Percent retained on the No. 200 sieve
3. Specific gravity

4. CaO heat evolution test.

The percent retained on a No. 325 sieve was determined for compliance with C-618 physical and uniformity specifications. The No. 325 sieve analysis was performed substantially in accordance with ASTM C-430, "Fineness of Hydraulic Cement by the No. 325 Sieve" (23). Briefly, a one gram sample of fly ash was placed on a calibrated No. 325 sieve under a 10 psi water stream for one minute. The only deviations from the standard test procedure were omissions of a pre-wetting and post-rinsing of the sample in the sieve.

The No. 200 sieve analysis was not performed in accordance with any standard specification. The test was designed to approximate what might be considered field conditions for comparison with the No. 325 sieve laboratory test. The test consisted of a 50 gram sample of ash being placed on a standard No. 200 sieve. A gently flowing stream of water was then run over the sample, while the sieve was moved with a slow wrist motion until all the minus 200 particles passed through the sieve. The specifics of this procedure are given in Appendix B.

The fly ash's specific gravity was also determined for compliance with ASTM C-618 in strict accordance to the standards set forth in ASTM C-311, "Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete" (8). Approximately 250 ml of kerosene were placed in a flask and the temperature of the flask stabilized in a water bath. Fifty grams of fly ash were then added to the flask and the specific gravity determined after the flask temperature was again allowed to stabilize in the bath.

The calcium oxide heat evolution test, like the No. 200 sieve analysis, was performed to examine its potential as a quick field test to determine fly ash variability. Research conducted in Poland discovered the heat evolution concept. There it was determined that a linear relationship existed between the CaO content of a fly ash and the rise in temperature that occurred when designated quantities of fly ash and hydrochloric acid were combined. In this test, 20 grams of fly ash were placed in an insulated container with 75 ml of 15 percent hydrochloric acid. A thermometer was inserted through the lid of the container, and the rise in temperature recorded. The temperature rise was processed through a linear relationship to determine the total calcium oxide present. The specifics of this test are also included in Appendix B.

The results of this first test sequence are found in Appendix C and summarized in Table 5. For each fly ash, this table gives the mean and standard deviation of the sieve analyses, specific gravity, and heat evolution tests. The temperature rises of the CaO heat evolution tests have already been reduced to show indicated mean CaO contents and variabilities.

Chemical Analysis Testing

The second test series involved the chemical oxide analysis of selected fly ashes by an outside laboratory. The chemical analysis was performed on 44 samples and might well be considered an extension of the variability study. The chemical analysis of 25 of the 44 samples was performed in strict accordance to ASTM C-311 (8). For

Table 5. Summary of variability testing.

Fly Ash	Statistic	% Retained No. 325 Sieve	% Retained No. 200 Sieve	Specific Gravity	CaO by Heat Evolution
D	Mean	17.3	8.7	2.57	24.2
	Std. Dev.	3.32	2.40	0.05	1.78
	n=102				
H	Mean	15.8	7.2	2.62	26.8
	Std. Dev.	1.79	1.42	0.03	1.36
	n=50				
M	Mean	29.6	13.7	2.27	9.8
	Std. Dev.	4.87	2.96	0.04	1.56
	n=74				
W	Mean	15.6	7.5	2.63	27.6
	Std. Dev.	3.70	2.18	0.05	0.88
	n=69				
B	Mean	15.8	6.6	2.56	18.0
	Std. Dev.	2.26	1.06	0.03	1.33
	n=47				

the remaining 19 samples, the concentrations of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and SO_3 were determined by atomic absorption instead of the wet chemistry analysis called for in ASTM C-311. This alternate analysis procedure was not expected to affect the validity of testing, since atomic absorption is generally considered the more accurate of the two methods (25).

The results of the chemical analysis are summarized in Table 6. Here again the means and standard deviations of the properties analyzed are presented for each individual ash. These results provide an understanding of the compositional natures and variabilities of the five ashes. In addition, this chemical analysis is crucial to providing insight into the causal factors of fly ash which contribute to the behavioral characteristics of blended cement mortars.

Performance Testing

The third test sequence was designed to examine the effects of fly ash on mortar compositions. The tests included:

1. Pozzolanic activity index
2. Water requirement
3. Time of initial set
4. Time of final set
5. Air content
6. Flow

The pozzolanic activity index (PAI) and water requirement (WR) were determined for one representative sample from each power plant.

Table 6. Summary of chemical oxide analysis.

Fly Ash	Statistic	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equivalent Na_2O	LOI
D	Mean	39.6	22.7	4.9	25.5	3.75	1.53	0.42	0.38
	Std. Dev.	2.94	1.67	0.76	3.51	1.02	0.38	0.27	0.26
	n=16								
H	Mean	35.2	21.9	6.4	27.5	4.55	2.32	0.73	0.40
	Std. Dev.	1.63	1.79	0.49	1.47	0.51	0.21	0.26	0.08
	n=7								
M	Mean	60.6	22.3	3.3	10.6	2.10	0.32	0.04	0.08
	Std. Dev.	2.30	3.61	0.14	4.54	0.10	0.28	0.03	0.04
	n=8								
W	Mean	33.9	22.8	5.6	29.1	3.86	3.09	1.17	0.40
	Std. Dev.	1.26	1.48	0.22	2.52	0.49	0.52	0.17	0.10
	n=7								
B	Mean	49.9	17.2	7.3	18.2	3.46	1.45	0.19	0.42
	Std. Dev.	1.05	0.37	0.32	0.36	0.13	0.04	0.03	0.10
	n=5								

The purpose of this spot testing was to gain some insight into these properties for each of the five plants.

The water requirement for each of the samples was determined in strict accordance with ASTM C-311. In brief, water was added to specified quantities of cement, sand, and fly ash for both a control mix and test mixes, until a flow of 107.5% ± 7.5% was obtained. The water requirement was then calculated from the following equation:

$$WR = \frac{\text{Volume of water for test mix}}{\text{Volume of water for control}} \times 100\ \%$$

The test for pozzolanic actitity index also followed ASTM C-311. This test was performed using the same mortar prepared in the water requirement testing. The mortars were placed in two-inch cube molds and cured 28 days according to specifications. An accelerated 7-day curing procedure currently under proposal to ASTM was also used. Both curing procedures cure the mortar cubes 1 day at 73°F, 95 percent relative humidity, but the accelerated method calls for curing the cubes 6 days at 150°F as opposed to 27 days at 100°F for the presently specified method. The PAI was then calculated using the following equation:

$$PAI = \frac{\text{Average compressive strength of test mix cubes}}{\text{Average compressive strength of control mix cubes}} \times 100\%$$

Table 7 displays the results of the water requirement and PAI testing. Note that all five ashes tested easily met the ASTM C-618 specifications.

The flow, air content, time of initial set, and time of final set

Table 7. Results of pozzolanic activity and water requirement testing.

Fly Ash	Sample No.	Water Requirement (% Control)	Pozzolanic Activity index 7 Day (% Control) [a]	Pozzolanic Activity Index 28 Day (% Control)
D	3-12	92	101	128
H	9	96	108	116
M	1-8	90	106	110
W	2-4	91	166	115
B	11-2	85	204	137
ASTM C-618 Specifications		max 105	min 50	min 75

a Accelerated pozzolanic activity index procedure under proposal.

were all examined for various mortar compositions. One fly ash sample was selected from each of the five sources and used to make mortars with water-cement ratios of 0.4, 0.5, and 0.6 by weight. For each water-cement ratio, mortar specimens were prepared with 0, 10, 20, and 30 percent replacements of fly ash by weight from each of the five plants. Therefore, 15 test specimens and one control were prepared for each water-cement ratio, and 48 samples were generated. In addition, two extra fly ash samples were selected from each of the five plants and used to prepare ten other mortar specimens, all with a 0.5 water-cement ratio, and 20 percent fly ash replacement. A total of 58 mortar specimens were thus prepared from which flow, air content, initial set and final set determinations were made. It was decided to investigate the effects of water-cement ratio and fly ash replacement percentage on the fresh properties; therefore, a wide range of mortar compositions was selected to insure adequate investigation of those two variables and to reveal any relationships that might be present.

The mortar specimens were mixed in a five gallon rotary mixer for four minutes after the cement and fly ash contacted the mixing water. The sand was slowly added between minute one and minute two in an effort to approximate ASTM C-305, "Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" (23). Upon completion of mixing, the flow test was performed, the time of set cylinders prepared, and the air content measured, in that sequence. From the time of mixing, it took from between 16 to 18 minutes to complete these operations.

The flow was determined using a standard flow table conforming to ASTM C-230 (8). The mortar sample was placed in a mold on top of the table, and the table allowed to drop from a height of half an inch, 25 times in 15 seconds. Flow was determined by the equation below:

$$\text{Flow} = \frac{\text{Average increase in base diameter (in)}}{4 \text{ (in)}}$$

Flow results are listed in Table 8.

The initial and final times of set were determined in accordance to ASTM C-403, "Time of Setting of Concrete Mixtures by Penetration Resistance", with two exceptions (8). ASTM C-403 called for the mortar tested to be sieved from a concrete sample, and this program used a straight mortar mixture. However, this irregularity is not anticipated to alter the effects of fly ash on setting times (26). Secondly, the specifications also called for three batches to be made for each test condition, but in this case, only one batch was made because of time constraints.

The results were obtained by measuring the fresh mortar's resistance to penetration by a needle. Initial set was the time associated with a resistance of 500 psi, and the final set time corresponded to a 4,000 psi resistance. Tables 9 and 10 list the initial and final set times for varying fly ash/cement proportions.

Finally, air content was measured in strict accordance with the American Association of State Highway and Transportation Officials (AASHTO) T-199, "Air Content of Freshly Mixed Concrete by the Chace Indicator" (27).

Table 8. Results of flow test on mortar samples.

Fly Ash	Sample No.	Flow for 0-30% Wt. Replacements of Cement by Fly Ash (% Increase in Sample Base)			
		0	10	20	30
water-cement ratio = 0.4					
D	4-10	11	24	28	48
H	17	11	30	29	32
M	1-24	11	31	22	35
W	2-12	11	27	26	46
B	11-2	11	22	32	48
water-cement ratio = 0.5					
D	3-12	33	--	59	--
D	4-10	33	55	48	61
D	5-3	33	--	50	--
H	1	33	--	58	--
H	9	33	--	61	--
H	17	33	55	56	51
M	1-3	33	--	51	--
M	1-8	33	--	55	--
M	1-24	33	51	56	62
W	2-1	33	--	52	--
W	2-4	33	--	55	--
W	2-12	33	45	52	58
B	7	33	--	56	--
B	15	33	--	58	--
B	11-2	33	55	60	61
water-cement ratio = 0.6					
D	4-10	55	55	80	78
H	17	55	53	76	84
M	1-24	55	59	80	86
W	2-12	55	59	74	76
B	11-2	55	65	83	85

Table 9. Test results for initial time of set of mortar samples.

Fly Ash	Sample No.	Initial Set Times for 0-30% Wt. Replacements of Cement by Fly Ash (Hrs.)			
		0	10	20	30
water-cement ratio = 0.4					
D	4-10	3.97	4.50	5.00	5.72
H	17	3.97	5.08	5.33	6.58
M	1-24	3.97	3.88	4.47	4.83
W	2-12	3.97	4.50	4.90	5.50
B	11-2	3.97	4.45	4.58	5.05
water-cement ratio = 0.5					
D	3-12	5.00	--	6.25	--
D	4-10	5.00	5.75	6.08	6.42
D	5-3	5.00	--	6.08	--
H	1	5.00	--	7.25	--
H	9	5.00	--	7.37	--
H	17	5.00	6.10	7.58	8.50
M	1-3	5.00	--	5.75	--
M	1-8	5.00	--	5.75	--
M	1-24	5.00	5.67	5.75	5.75
W	2-1	5.00	--	6.33	--
W	2-4	5.00	--	6.33	--
W	2-12	5.00	5.75	6.67	6.42
B	7	5.00	--	5.92	--
B	15	5.00	--	6.08	--
B	11-2	5.00	5.53	6.08	6.17
water-cement ratio = 0.6					
D	4-10	5.75	5.93	6.83	7.92
H	17	5.75	5.92	8.70	9.33
M	1-24	5.75	5.42	6.55	7.00
W	2-12	5.75	6.17	7.50	8.33
B	11-2	5.75	6.17	7.37	7.67

Table 10. Test results for final time of set of mortar samples.

Fly Ash	Sample No.	Final Set Times for 0-30% Wt. Replacements of Cement by Fly Ash (Hrs.) 0	10	20	30
water-cement ratio = 0.4					
D	4-10	6.47	6.42	7.08	8.05
H	17	6.47	7.00	7.83	9.83
M	1-24	6.47	6.00	6.77	7.22
W	2-12	6.47	6.30	7.30	8.03
B	11-2	6.47	6.50	6.62	7.23
water-cement ratio = 0.5					
D	3-12	7.42	--	8.58	--
D	4-10	7.42	7.92	8.50	9.45
D	5-3	7.42	--	8.75	--
H	1	7.42	--	10.17	--
H	9	7.42	--	10.97	--
H	17	7.42	8.92	11.05	12.17
M	1-3	7.42	--	9.17	--
M	1-8	7.42	--	8.42	--
M	1-24	7.42	7.83	8.67	8.58
W	2-1	7.42	--	9.17	--
W	2-4	7.42	--	9.25	--
W	2-12	7.42	8.25	9.33	9.67
B	7	7.42	--	8.33	--
B	15	7.42	--	8.50	--
B	11-2	7.42	7.83	8.45	9.58
water-cement ratio = 0.6					
D	4-10	8.58	8.83	9.92	11.17
H	17	8.58	8.87	11.75	12.92
M	1-24	8.58	8.17	10.17	10.00
W	2-12	8.58	9.25	10.87	11.67
B	11-2	8.58	9.33	10.75	10.58

A small amount of mortar is placed in a brass cup and inserted into the Chace indicator. The indicator is filled with alcohol to a prescribed mark, inverted, and the mortar sample allowed to disintegrate. Entrained air is determined by the change in the level of alcohol within the indicator multiplied by a factor to compensate for different amounts of mortar per cubic yard of concrete. The air contents determined for 15 cubic feet of mortar per cubic yard of concrete are given in Table 11.

Table 11. Test results for air content for 15 cubic feet of mortar per cubic yard of concrete.

Fly Ash	Sample No.	Air Content for 0-30% Wt. Replacements of Cement by Fly Ash (% by Volume) 0	10	20	30
water-cement ratio = 0.4					
D	4-10	4.1	3.9	4.2	3.9
H	17	4.1	3.8	3.9	4.1
M	1-24	4.1	4.3	4.3	4.2
W	2-12	4.1	3.9	4.0	3.7
B	11-2	4.1	3.7	4.1	3.8
water-cement ratio = 0.5					
D	3-12	4.2	-	4.3	-
D	4-10	4.2	4.3	4.5	4.0
D	5-3	4.2	-	3.8	-
H	1	4.2	-	4.1	-
H	9	4.2	-	4.2	-
H	17	4.2	4.3	4.2	4.2
M	1-3	4.2	-	4.0	-
M	1-8	4.2	-	4.0	-
M	1-24	4.2	4.7	4.3	4.3
W	2-1	4.2	-	4.3	-
W	2-4	4.2	-	4.5	-
W	2-12	4.2	4.2	4.2	4.2
B	7	4.2	-	3.8	-
B	15	4.2	-	4.0	-
B	11-2	4.2	4.0	3.8	3.5
water-cement ratio - 0.6					
D	4-10	4.7	4.2	3.9	3.9
H	17	4.7	4.4	3.9	3.8
M	1-24	4.7	4.7	3.9	3.8
W	2-12	4.7	4.3	4.1	4.1
B	11-2	4.7	4.0	3.8	3.5

CHAPTER 4

ANALYSIS OF RESULTS

The analyses of data can be divided into four sections. First, an analysis of variability was performed on the physical and chemical properties of fly ash from the five plants. Second, a visual inspection was undertaken in search of any other pertinent information that could not be obtained by other methods. Third, regression analyses were used to uncover any relationships occurring between physical, chemical and behavioral characteristics. And fourth, an analysis of correlations that might exist between physical and chemical properties was performed.

Analysis of Variability

Tables 5 and 6 list the means and standard deviations for the ashes tested. The variation in fly ash from both plants H and B was observed to be minimal, while the plant M fly ash exhibited an extremely variable nature. Plant D and W ashes also had a tendency to range in composition, but to a lesser degree than plant M.

Two of the fly ash sources now process their ash. Plant B uses an air separator to remove from 15 to 30 percent of the coarser particles. Plant D, on the other hand, uses a recently developed skimming technique which skims off the larger particles that tend to flow in the lower layers of ash as the ash passes through the ductwork exiting the boiler. A comparison of plant D processed and unprocessed ash revealed substantially no difference in ash variability. No unprocessed fly ash from plant B was available to compare with the processed; however, because plant B ash is lignitic, the composition of unprocessed ash is expected to be quite variable. Processing the plant B fly ash appears to transform a variable lignite ash into an ash that is quite uniform.

Table 12 gives the number of samples that failed to comply with C-618 uniformity specifications for each plant. To arrive at the figures given in this table, it was assumed that the interval of sampling approximated the testing intervals called for in C-618. The allowable variations were then determined from the previous samples according to specifications. This table again points out that plant M and W ashes demonstrate significantly higher variabilities, while the fly ashes from plants B and H remain fairly constant. The plant D ash falls somewhere between the two extremes.

Plant D

The fly ash from plant D exhibited several characteristics worthy of at least precautionary attention (Tables 5 and 6). First, the variation of the fineness and specific gravity are quite high. The MgO content draws special attention because the mean value of 3.75 percent and standard deviation of 1.02 percent cause it to range very near the 5.0 percent maximum allowed. The variation in LOI is also noteworthy. Although the mean LOI of 0.38 is quite small, values ranged from 0.02 to 0.88, which could vary the amount of entrained air in concrete.

Table 12. Summary of samples failing to meet ASTM C-618 uniformity specifications for specific gravity and fineness.

Fly Ash	Number of Failures: No. 325 Sieve	Number of Failures: Specific Gravity	Number of Failures: Total	% Failing
D	5	2	7	6.9
H	1	0	1	2.5
M	15	1	16	23.5
W	11	0	11	16.9
B	3	0	3	6.4

Plant H

The plant H ash demonstrated a very stable nature, exhibited by only one failure of the C-618 uniformity requirements (Table 12); however, the ash also possessed one very pronounced deficiency. The MgO content was extremely high,with a mean of 4.55 percent, and three of the seven samples analyzed contained the allowed maximum of 5.0 percent or greater. The alkali content of the plant H ash was also rather high accompanied by a substantial standard deviation. If this ash were used with reactive, siliceous aggregates, further attention would need to be directed toward this property.

Plant M

Plant M fly ash was the most inconsistent ash analyzed; however, none of its chemical constituents ever approached violating the chemical requirements. Both the CaO and Al_2O_3 were highly inconsistent, but no specification currently regulates these quantities. The chief concern of this ash was its fineness. The plant M fly ash was by far the coarsest examined with 29.6 percent retained on the No. 325 sieve. The variability of the fineness also contributed to the undesirable nature of the ash, the standard deviation being 4.87 percent retained - which itself was extremely near the 5.0 percent variation limit. These values explain the high failure percentage shown for plant M ash in Table 12. The variation of plant M's specific gravity was just one other indication of the fly ash's overall variable nature.

Plant W

Fly ash from plant W also showed some signs of variability; however, the variable nature indicated by the fineness and specific gravity was not seen in the overall plant variability, that is, the amounts of other compounds remained very uniform. Plant W did exhibit substantially large alkali, MgO and SO_3 concentrations, but even though the quantities of these compounds approached specification limits, they never exceeded them.

Plant B

The plant B fly ash demonstrated a very consistent nature. The only point of concern was the 3.45 percent mean concentration of MgO; even still, the standard deviation for this compound was only 0.13 percent,which alleviates some of the concern. Overall, the potential for this ash from, a chemical, physical, and uniformity standpoint is very promising.

Two general observations pertaining to these sub-bituminous and lignite fly ashes surround the pozzolanic activity index, the water requirement, and the MgO concentrations. From a performance standpoint, all five ashes demonstrated PAI's over 110 and WR's less than 96.5 which is commendable (Table 7, page 37). However, high MgO concentrations are always present. Although for the most part, the amounts remain within chemical requirements, the high MgO concentrations are still there, and deleterious activity in hardened concrete could result, as discussed in Chapter 2.

A final comment is that the variabilities of the No. 200 and No. 325 sieve analyses, specific gravity, and CaO content by the heat evolution method, usually present a fairly close representation of an ashes total variable nature.

Visual Analysis

Many of the collected data did not lend themselves to the correlation, regression, or even variability analyses by reason of small sample size and inconsistency of sample compositions. To provide an effective analysis of these data, a procedure was used that compared the relative rankings of each plant with respect to behavioral characteristics and physicochemical properties. For each water-cement ratio and ash replacement combination, the entrained air, flow, and set times of the five fly ashes were ranked from one to five (lowest value to highest). The rankings were then averaged for each ash to determine the relative ranks and listed in Table 13. Initial and final set are combined into one average since their individual relative rankings were identical.

From Table 13 several pertinent pieces of information emerge. First, it appears that a specific hierarchy of setting times exists among the five ashes. It was obvious during testing that the plant M ash was the quickest setting ash. At 10 percent replacement it was usually seen to set quicker than a 100 percent portland cement mixture.

The samples made with plant H fly ash were consistently the last samples to set, retarding the final set as much as 4 1/2 hours at 30 percent replacement. The remaining three ashes usually set in the

Table 13. Average and relative rankings of flow, set, and air content by plant for the nine mortar designs tested.

Fly Ash	Flow		Air Content		Set	
	Average	Relative	Average	Relative	Average	Relative
D	3.1	IV	2.9	IV	2.9	III
H	2.4	II	2.4	II	4.7	V
M	2.8	III	4.2	V	1.4	I
W	2.0	I	2.8	III	3.7	IV
B	3.9	V	1.8	I	2.3	II

order of plant B, plant D, and plant W. Replacement of cement by fly ash almost invariably delayed initial and final set as replacement percentages were increased. Figure 4 illustrates the typical retarding action of fly ash as increasing quantities of cement are replaced. No other external factors such as water-cement ratio were observed to affect relative times of set.

The air contents of the various fly ashes did not exhibit quite the distinct nature seen in the setting behavior. It was discernible that plant B ash consistently demonstrated lower entrained air contents while plant M ash usually contained higher amounts of entrained air for a given amount of air entraining agent. The other three fly ashes fell somewhere between these two extremes and appeared to contain approximately the same amounts of entrained air. Again, neither the water-cement ratio or any other external factors were seen to affect the air contents results.

Flow tendencies were also more difficult to recognize than setting time characteristics. Fly ash from plant B quite noticeably exhibited the highest flows. The lower flow ranges were found within plant H and W ashes. The remaining two fly ashes from plants D and M indicated intermediate flows. Higher water-cement ratios, quite understandably, contributed to increasing flows. Figure 5 illustrates the flows determined for a typical fly ash at three different water-cement ratios and fly ash replacement percentages. Increasing replacements of cement with fly ash consistently increased the flow even though larger volumes of fly ash replaced the cement. This is because the spherical shape of ash particles act as tiny ballbearings which

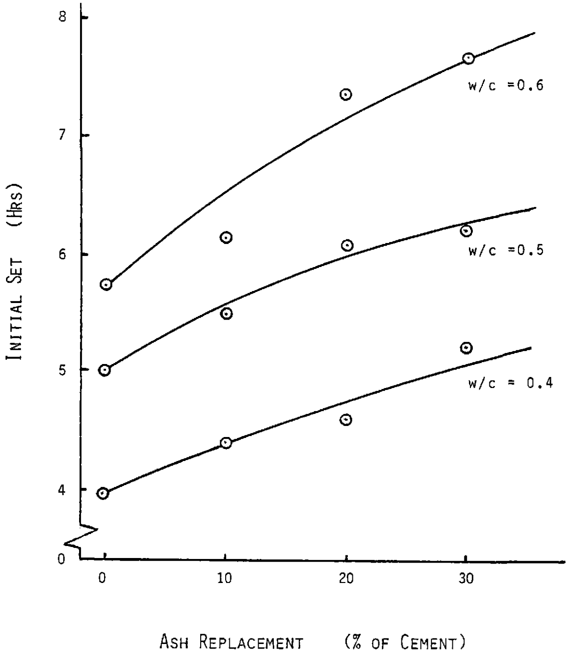

Figure 4. Initial set results of plant B fly ash.

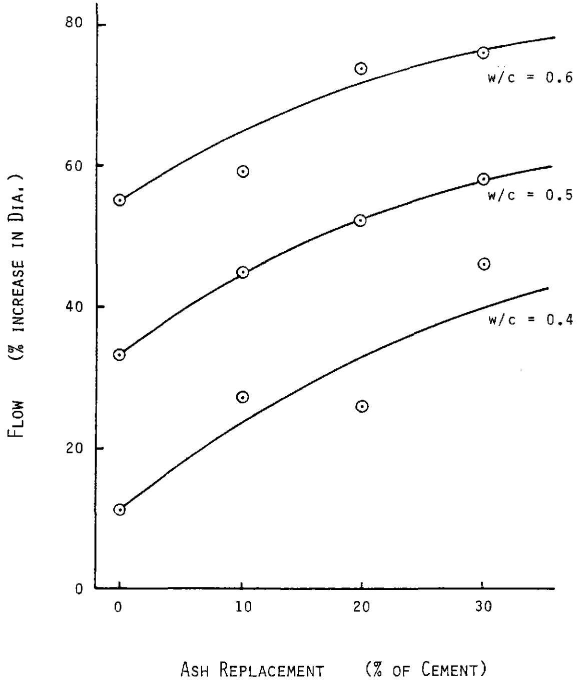

Figure 5. Flow results of plant W fly ash.

lubricate a mix.

The average rankings of flow, air content, and set times were ranked along with the other known properties of each ash. These relative rankings are summarized in Table 14 and illustrated in Figure 6 to show the correlations that were indicated between physicochemical properties and behavioral characteristics. From this analysis, it appears that larger SiO_2 and smaller CaO contents will reduce the set time. It is possible that the specific gravity is also related to set; however, it is more likely that the correlation between this property and set times is coincidental with the correlations between specific gravity, SiO_2 and CaO.

The SO_3 and MgO concentrations were also observed to be strongly correlated with the average set time rankings. In portland cement concrete, higher concentrations of these compounds are known to retard set, so their appearance to be linked with higher set times here seems ligitimate. If these compounds, however, are indeed delaying the set times, further study is warranted to determine if they are also causing deleterious expansions in hardened concrete as they have also been known to do.

Air content was strongly associated with the fineness, LOI, Fe_2O_3, and alkali contents. Lower finenesses, and LOI percentages strongly coincided with high entrained air contents which reinforces accepted findings from the literature. It was also observed that lower Fe_2O_3 and higher alkali concentrations could possibly contribute to high quantities of entrained air.

Flow was not strongly linked to any of the fly ash properties;

Table 14. Relative rankings of physicochemical and behavioral characteristics for the five ashes tested.

Fly Ash	Flow	Air Content	Set	PAI	WR	Ret. No. 325	SG	LOI	SiO_2	Al_2O_3	Fe_2O_3	SUM	CaO	MgO	SO_3	Na_2O
D	IV	III	III	II	IV	IV	III	II	III	IV	II	III	III	III	III	II
H	II	II	V	I	V	I	IV	III	II	II	IV	I	IV	V	IV	III
M	III	V	I	V	II	V	I	I	V	III	I	V	I	I	I	I
W	I	III	IV	III	III	I	V	III	I	IV	III	II	V	IV	V	IV
B	V	I	II	I	I	I	II	V	IV	I	V	IV	II	II	II	V

	% Ret. No. 325	SO_3	Spec. Grav.	Na_2O Equiv.	LOI	MgO	SiO_2	Al_2O_3	Fe_2O_3	SUM	CaO
Set Time		O	O			X	◇O			◇X	
Air Content	X			O	◇X				◇X		
Flow			◇O				O				◇O
Pozzolanic Activity Index											
Water Requirement											

$$SUM = SiO_2 + Al_2O_3 + Fe_2O_3$$

X Very Strong Correlation

O Strong Correlation

◇ Inverse Correlation

Figure 6. Correlations determined between physicochemical properties and behavioral characteristics by visual ranking.

however, the results of this analysis indicate that it might be tied to the SiO_2, CaO, and specific gravity properties. High silicate, lower calcium oxide, and reduced specific gravity appear to be associated with increased flows.

This procedure uncovered no significant correlations involving either the water requirement or the pozzolanic activity index. However, only one sample was tested from each source, and the probability of variations affecting correlation results is substantial.

Regression Analyses

The regression analyses were performed to provide: 1) a means of estimating significant ash properties from field tests such as the No. 200 sieve analysis and CaO heat evolution test, and 2) isolation of the fly ash elements which seem to control flow, air content, and set times.

A major finding of this research was that the percent retained on a No. 325 sieve, the CaO content, and the specific gravity could be accurately predicted from the results of the No. 200 sieve analysis and CaO heat evolution test.

The 44 laboratory determinations of CaO were regressed against the temperature change (ΔT) of the CaO heat evolution test to produce the following relationship:

$$CaO = 0.395\ (\Delta T) + 3.234$$

$$R^2 = 0.88$$

Eighty-eight percent of the variance in actual CaO content could be accounted for by the above equation, and no improvement was seen when the No. 200 sieve results were included.

Regression analyses of the specific gravity and percent retained on a No. 325 sieve were done using all 342 samples. Eighty-six percent of the variance in the No. 325 sieve results could be accounted for by the No. 200 sieve analysis. The accuracy of the model was improved to 92 percent when the CaO heat evolution results were included. The optimum relationship is given below:

$$\text{Percent retained No. 325} = 1.399\ (\text{percent retained No. 200}) - 0.116\ (\Delta T) + 11.864$$

$$R^2 = 0.92$$

Both the No. 200 sieve analysis and the CaO heat evolution test contributed to the determination of the specific gravity. Eighty-six percent of the variance in specific gravity could be accounted for by the following equation:

$$\text{Specific Gravity} = 0.006\ (\Delta T) - 0.0095\ (\text{percent retained No. 200}) + 2.330$$

$$R^2 = 0.88$$

Using these equations, close approximations of fineness, CaO content, and specific gravity can be quickly obtained from the No. 200 sieve and CaO heat evolution tests. These findings will contribute greatly to the expedient determination of fly ash uniformity in the field.

Further research should be directed toward developing uniformity requirements which utilize the No. 200 sieve analysis and CaO heat evolution tests.

A second multiple regression approach was adopted to determine the chemical and physical properties of fly ash which appear to govern the flow, air content, initial set, and final set of a fly ash/portland cement mortar. The 15 samples tested at water-cement ratios of 0.5 and 20 percent fly ash replacement were used because they reduced the complexity of the analysis by limiting the number of variables considered. The actual equations derived by this procedure are of little significance due to the small sample size, and thus, are not included; however, the functional relationships determined are given below:

$$\text{Initial set} = f\,(Al_2O_3,\ Fe_2O_3)$$

$$R^2 = 0.867$$

$$\text{Final set} = f\,\left(Al_2O_3,\ Fe_2O_3,\ \frac{1}{SiO_2}\right)$$

$$R^2 = 0.867$$

$$\text{Air Content} = f\,\left(\text{No. } 325,\ \frac{1}{LOI},\ \frac{1}{MgO},\ \frac{1}{SiO_2}\right)$$

$$R^2 = 0.891$$

Note that the most significant model of air content indicated that four fly ash properties (LOI, fineness, SiO_2, MgO) accounted for 89.1 percent of the entrained air content variation. As the fineness, LOI, SiO_2, and MgO increase, the entrained air content appears to decrease. It also stands to reason that, if indeed the above compounds do affect air content, large variations of these compounds can cause entrained air to fluctuate.

The initial time of set was shown to be dependent on the presence of aluminate and ferrite, which together accounted for 87 percent of the variation in initial set time. Higher concentrations of these elements appeared to prolong initial set. This conclusion is not in keeping with the effects of high aluminate in portland cement, where flash setting is a result of high Al_2O_3 concentrations.

The most significant relationship found for final set also involved Fe_2O_3 and Al_2O_3. Again, as with initial set, increases in aluminate and ferrite percentages appeared to lengthen the time to final set. The analysis of final set times also indicates that an additional element, SiO_2, was significant. This implies that the effects of SiO_2 are not significant within the first hours of setting; however, with the passing of time, the presence of SiO_2 becomes more pronounced acting to accelerate the time to final set. These silicate compounds were linked earlier to reduced set times, and in light of these results, it is strongly suggested that the SiO_2 concentration is indeed related to the setting characteristics of a fly ash/cement mortar.

A relationship for flow is not included because none of the known properties were shown to have any effect on this behavioral characteristic.

Correlation Analyses

The purpose of the correlation analyses was to surface the interconnected nature of the characteristics tested. Use of correlation analyses to investigate further or perhaps even estimate a given ash characteristic through knowledge of a second property could be a substantial contribution to ash utilization.

Analysis of the correlations between physical and chemical properties was done using Pearson, Spearman, and Kendall correlation methods (28, 29, 30). The results of the significant correlations for these analyses are presented in Figures 7 through 9. In addition, the Pearson correlation coefficients of the results from the four tests performed on all 342 samples are included as Figure 10.

The Pearson method is by far the most accepted and therefore will be the basis for the majority of this discussion. The Spearman and Kendall analyses were undertaken merely as reinforcement of the Pearson approach, and when referred to will be mentioned specifically by name. All correlation values are on a scale of 0 to 1.00, zero being no correlation and 1.00 indicating a perfect correlation. The associated probabilities for the given correlations to occur by chance are denoted by geometric symbols. An 'N' within the box indicates an inverse correlation.

From just a quick glance at Figures 7 through 10, it is evident that a large degree of correlation is indicated between several of the properties analyzed. A larger sample size could conceivably reduce the number of significant correlations and this should be considered

	% Ret. No. 200	Spec. Grav.	CaO by Heat Evol.	LOI	Moisture	SiO_2	Al_2O_3	Fe_2O_3	SUM*	CaO	MgO	SO_3	Equiv. Na_2O
% Ret. No. 325	● .93	● N .80	● N .76	□ N .44		● .71		● N .59	● .75	● N .70	● N .62	● N .66	□ N .44
% Ret. No. 200		● N .68	● N .59	/ N .33		● .57		● N .57	● .61	● N .56	N .46	● N .58	□ N .42
Spec. Grav.			● .89	● .56		● N .87		● .65	● N .88	● .88	● .58	● .78	● .59
CaO by Heat Evol.				● .50		● N .96		□ .46	● N .94	● .94	● .68	● .81	● .68
LOI					/ .37	● N .55		● .51	● N .53	● .55		● .49	□ .40
Moisture							□ N .47						
SiO_2								● N .53	● .96	● N .96	● N .67	● N .86	● N .74
Al_2O_3								□ .41					
Fe_2O_3									● N .55	□ .46	● .57	● .58	
SUM*										● N .97	● N .65	● N .85	● N .68
CaO											● .54	● .83	● .70
MgO												● .53	
SO_3													● .85

Probabilities of Correlations Occurring by Chance:

● $P < .001$

□ $.001 \le P < .01$

/ $.01 \le P < .05$

N = Inverse Correlation

*SUM = $SiO_2 + Al_2O_3 + Fe_2O_3$

Figure 7. Pearson correlation analysis of physical and chemical properties (44 samples).

	% Ret. No. 200	Spec. Grav.	CaO by Heat Evol.	LOI	Moisture	SiO_2	Al_2O_3	Fe_2O_3	SUM*	CaO	MgO	SO_3	Equiv. Na_2O
% Ret. No. 325	● .81	● N .51	● N .55	/ N .36		● .54		□ N .47	● .53	□ N .48	● N .51	● N .57	□ N .45
% Ret. No. 200		□ N .44	/ N .37			/ .37		● N .51	/ .36	/ N .34	/ N .30	□ N .48	● N .41
Spec. Grav.			● .70	□ .48		● N .71		● .50	● N .72	● .75	/ .35	● .68	● .37
CaO by Heat Evol.				□ .42		● N .87		/ .33	● N .84	● .83	● .51	● .77	● .78
LOI					/ .38	● N .51		● .51	● N .49	● .52		● .52	● .52
Moisture							□ N .48						
SiO_2								● N .51	● .95	● N .96	● N .50	● N .89	● N .83
Al_2O_3								/ N .39					
Fe_2O_3									□ N .49	□ .41	● .52	● .61	□ .45
SUM*										● N .96	● N .52	● N .84	● N .75
CaO											● .60	● .82	● .78
MgO												□ .49	
SO_3													● .83

Probabilities of Correlations Occurring by Chance:

● $P < .001$

□ $.001 \le P < .01$

/ $.01 \le P < .05$

N = Inverse Correlation

*SUM = $SiO_2 + Al_2O_3 + Fe_2O_3$

Figure 8. Spearman correlation analysis of physical and chemical properties (44 samples).

	% Ret. No. 200	Spec. Grav.	CaO by Heat Evol.	LOI	Moisture	SiO_2	Al_2O_3	Fe_2O_3	SUM*	CaO	MgO	SO_3	Equiv. Na_2O
% Ret. No. 325	● .68	● N .37	● N .40	/ N .23		● .39		□ N .34	● .38	□ N .35	● N .36	● N .42	□ N .32
% Ret. No. 200		● N .34	□ N .29			□ .29		● N .40	/ .27	/ N .26		□ N .36	□ N .31
Spec. Grav.			● .54	□ .36		● N .55		□ .35	● N .57	● .59	/ .27	● .55	● .42
CaO by Heat Evol.				□ .29		● N .71		/ .24	● N .65	● .69	● .38	● .61	● .59
LOI					/ .28	● N .36		● .39	● N .36	● .39		● .36	□ .34
Moisture							□ N .37						
SiO_2								● N .38	● .81	● N .83	□ N .34	● N .72	● N .65
Al_2O_3								□ N .30					
Fe_2O_3									● N .37	□ .32	□ .35	● .40	□ .29
SUM*										● N .85	● N .39	● N .67	● N .58
CaO											□ .30	● .68	● .60
MgO												□ .34	
SO_3													● .64

Probability of Correlation Occurring by Chance:

● $P < .001$

□ $.001 \le P < .01$

/ $.01 \le P < .05$

N = Inverse Correlation

*SUM = $SiO_2 + Al_2O_3 + Fe_2O_3$

Figure 9. Kendall correlation analysis of physical and chemical properties (44 samples).

	%Retained No. 200 Sieve	Specific Gravity	CaO by Heat Evolution
% Retained No. 325 Sieve	.929	N .831	N .784
%Retained No. 200 Sieve		N .722	N .649
Specific Gravity			.909

N = Inverse Correlation

Probability of Chance Occurance:
P < .0001 for all values

Figure 10. Pearson correlation analysis of variability test results (342 samples).

for future analyses. At this point, it should also be mentioned that a correlation does not necessarily mean a relationship, so extreme care was exercised by the author and should be used by the reader in drawing conclusions.

The greatest benefit from knowledge of correlations can be gained when the knowledge is related to properties which are quickly and consistently obtained from field tests. For this reason, the correlations concerning the CaO heat evolution test and the No. 200 sieve analysis are of prime interest.

The CaO heat evolution test was reported earlier to very accurately approximate actual CaO content. The Pearson analysis substantiates this conclusion with a Pearson correlation coefficient (r-value) of 0.94. The No. 200 sieve analysis was used to give a quick indication of fineness, and as such, it is very closely related to the No. 325 sieve analysis evidenced by an r-value of 0.93. Correlating other properties to these expedient field tests would be quite helpful.

The sieve analyses are tied very close to other ash characteristics. High negative or inverse correlations were found between the percent retained on a No. 325 sieve and both specific gravity and CaO content. This indicates that finer ashes, higher calcium contents, and heavier unit weights are all somehow interlinked. A very strong positive correlation exists between percent retained and the sum of silicates, aluminates, and ferrites (SUM), coarser ashes usually occurring in higher quantities of the SUM components. Further examination reveals that the correlations involving SUM elements seem to be almost exclusively governed by the silicate content; as the silicate quantities fluctuate, the SUM contents do likewise. The apparent reasons for such a tight relationship are the small quantities of iron present, and an extremely non-variable nature exhibited by the aluminates.

Perhaps one of the more significant correlations surrounds the deleterious compounds (LOI, Na_2O equivalent, SO_3, and MgO). The analysis indicated that these compounds usually increased or decreased as a unit. The ashes which demonstrated higher finenesses, higher specific gravities, higher calcium contents, and lower quantities of silicates, were accompanied by larger LOI, alkali, SO_3, and MgO values.

By this time a pattern was seen to develop. The correlations that appear to exist are more tightly interwoven than might be first anticipated. Figure 11 is intended to demonstrate the interconnected nature of ash properties as those properties range from low to high values. This simplified figure illustrates how an ash with, for example, a high calcium oxide content usually exhibits higher LOI, MgO, alkali, and SO_3 levels, larger specific gravities, smaller particle sizes, and lower silica contents. Continuing with CaO content as an example, when lower calcium oxide quantities are observed, lesser amounts of the deleterious substances are encountered also, accompanied by lower specific gravities. In addition, the particle size increases as does the silica content. This is the overall picture that the correlation analyses appears to paint.

Figure 12 is included to highlight the properties which exhibit extremely strong correlations. Here the interconnected natures of

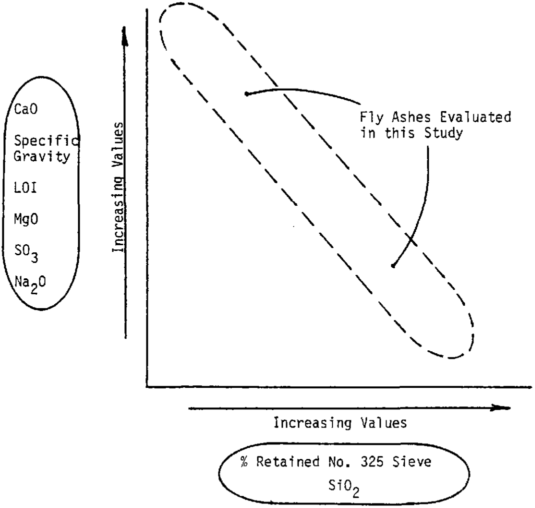

Figure 11. Compositional tendencies of ashes investigated.

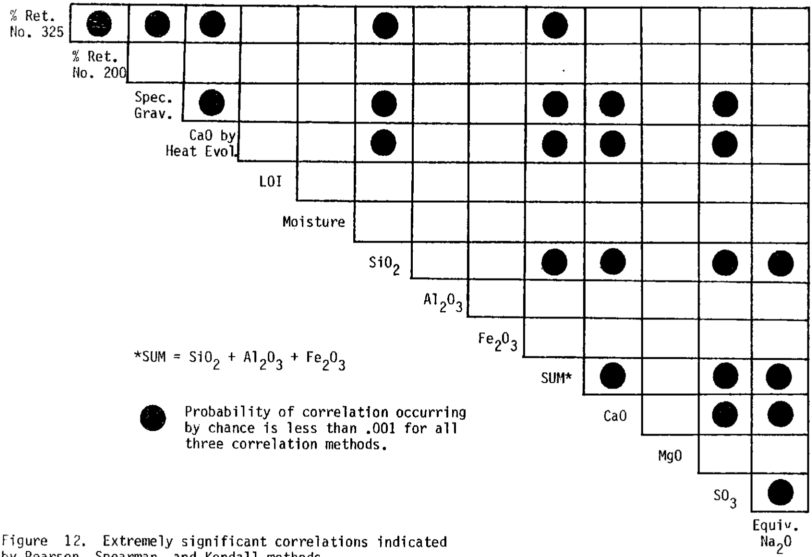

Figure 12. Extremely significant correlations indicated by Pearson, Spearman, and Kendall methods.

fineness, specific gravity, CaO, and SiO_2 can be clearly seen. The dependency of the SUM quantities on variance of SiO_2 has already been established, so that when correlations with SiO_2 are mentioned, correlations with the SUM constituents may be inferred. The very high negative correlation between SiO_2 and CaO appears to stem from the compositional nature of fly ash. The SiO_2 and CaO components are the only major constituents which vary significantly, all other components being relatively stable when compared to these two. The analysis indicates that as CaO is found to increase or decrease the difference is compensated for by SiO_2. Because of this strong inverse correlation, the SiO_2 always exhibits opposite correlations of the same magnitude as the CaO correlations.

Two deleterious substances were also strongly correlated with the calcium and silica contents. Both the alkali and SO_3 concentrations appeared to rise with increasing CaO, decreasing SiO_2 percentages. Larger amounts of SO_3 were also connected with higher specific gravities; however, this correlation is probably coincidental, since the relatively small quantities of SO_3 should not significantly affect unit weight.

Knowledge of such properties as CaO, specific gravity, and fineness are especially useful because of the strong interrelationships indicated with other ash properties evidenced by this correlation analysis. These correlations used jointly with the relationships established by the regression analysis can provide a basic understanding of an ash without detailed laboratory analysis. In conclusion, this analysis did tend to be exploratory in nature, and from the results, several additional points could be further developed to substantiate or refute the indications brought to light here.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the results of this study, the following conclusions can be drawn. These conclusions relate to the specific ashes investigated, and generalizations may not be warranted.

1. Fly ash exhibits a quite variable nature, but not to the extent that might be expected from a waste product.

2. The CaO heat evolution test provided an accurate indication of the total CaO present in a fly ash.

3. The specific gravity and percent retained on a No. 325 sieve were also accurately estimated from the results of the CaO heat evolution test and the No. 200 sieve analysis.

4. The total variable nature of the fly ashes were closely approximated by the variabilities of the No. 200 sieve analysis, and the CaO heat evolution test.

5. Fly ash processing techniques can substantially improve the characteristics of a fly ash,depending largely on the type of processing and individual nature of the ash to be processed. Processing with an air separator was observed to produce a more uniform ash, while the scalping method under development has yet to be proven with respect to variability.

6. The MgO contents of sub-bituminous and lignite fly ash exist in quantities that warrant close attention.

7. The Pozzolanic Activity Indices and Water Requirements of the five fly ashes treated were found to be quite favorable.

8. A very strong correlation is indicated between CaO, SiO_2, specific gravity, fineness, LOI, MgO, SO_3, and Na_2O alkali equivalent. Higher quantities of MgO, SO_3, LOI, CaO, and Na_2O equivalent are seen together with larger specific gravities and lower values of SiO_2 and percent retained on a No. 325 sieve.

9. Extremely strong correlations were seen between SiO_2, CaO and specific gravity. The SiO_2 and CaO components are the only major constituents which vary significantly; as CaO content is found to increase or decrease, the difference is compensated for by SiO_2. Large specific gravities also occur when higher CaO contents are present.

10. No significant degree of correlation was found between alkali contents and fineness - an opposite finding to that suggested by the North Dakota study.

11. Water-cement ratios do not appear to affect the relative performance of the five ashes tested.

12. The inclusion of fly ash in cement mortars almost invariably retards the time of set. Some fly ashes may act to accelerate the set times at lower replacement percentages, but as the replacement percentages rise above 10 percent, a retarding action takes precedence.

13. The concentrations of Al_2O_3 and Fe_2O_3 were indicated to strongly influence both initial and final set times, with higher amounts of these compounds retarding the set.

14. The SiO_2 was indicated to have an accelerating effect on the

final set times. Its effects on the early setting behavior appeared less pronounced,suggesting that the results of the silicate reactions are not seen in the first hours after mixing. The CaO and specific gravity also exhibited some correlation with set time; however, this is most probably due to the mutual correlation with SiO_2 mentioned above. The MgO and SO_3 were also observed to be correlated with increased set times,which is expected since the same action occurs in 100 percent portland cement concrete.

15. Increasing replacements of cement with fly ash consistently increased the flow even though larger volumes of fly ash were used in place of the cement.

16. Flow was not strongly linked to any of the fly ash properties; however, this study did reveal that there might be some connection between flow and the SiO_2, CaO, and specific gravity values. High silicate, lower calcium oxide, and reduced specific gravity appear to be associated with increased flow.

17. The fluctuation of air content was found to be strongly correlated with the fineness and LOI of a fly ash. Higher finenesses and LOI values appeared to reduce the amount of entrained air. In addition, the analyses suggested that increased alkali concentrations and decreased SiO_2, MgO, and Fe_2O_3 quantities effected higher entrained air contents.

Recommendations

The following recommendations arise from this research:

1. The CaO heat evolution test and No. 200 sieve analysis should be seriously considered for use as expedient fly ash quality control methods both at the power plant and just prior to utilization.

2. Further research is needed to substantiate the validity of the pozzolanic activity index indications with respect to actual concrete strengths.

3. Further correlation and regression analyses should incorporate a larger number of samples from a wider range of power plants to increase the validity of results.

4. Additional research is urged to establish the effects that high MgO and SO_3 quantities of sub-bituminous and lignite fly ashes have on the performance of hardened concrete.

5. The latent effects of fly ash on the entrained air content of concrete 45 minutes to 1 1/2 hours after mixing begins would be valuable.

6. Future research should emphasize the effects that varying cement replacements by fly ash have on the behavioral characteristics of concrete.

7. This research is largely exploratory in nature. The results are, among other things, intended to provide an initial insight into the compositional effects of fly ash on portland cement concrete. From here, the author strongly suggests additional research be focused on the individual conclusions brought to light.

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APPENDIX A

ANALYSIS OF RAW MATERIALS

Table A-1. Gradation of sand used to determine water requirement and pozzolanic activity index.

Sieve Number	Percent Retained	ASTM C-311 Specification
16	0	0
30	2.0	2 ± 2
40	29.0	30 ± 5
50	76.5	75 ± 5
100	97.5	98 ± 2

Table A-2. Gradation of sand used to prepare mortar samples.

Sieve Number	Percent Retained	ASTM D-1556[a] Specification
10	0	< 4
16	3.5	
30	52.5	
40	91.5	
50	99.0	
100	100.0	
200	100.0	> 96

a This sand specification (ASTM D-1556) was selected for no other reason than to use a standard sand.

Table A-3. Compliance of MB AE-10 air entraining admixture with ASTM C-260 "Standard Specification for Air Entraining Admixtures for Concrete".[a]

Criteria	Control	MB AE-10	ASTM C-260 Specification
Cement Content (bags)	5.50	5.51	5.50 ± 0.05
Air Content (%)	5.4	5.2	5.0 - 6.0
Slump (in)	2.75	2.75	2.5 ± 0.5
Time of Set (Hr : Min)			
Initial	5:10	5:05	Control ± 1:15
Final	7:10	7:05	Control ± 1:15
Compressive Strength (% Control)			
3 Day		102	90 (min)
7 Day		99	90 (min)
28 Day		101	90 (min)
6 Month		102	90 (min)
1 Year		-	90 (min)
Flexural Strength (% Control)			
3 Day		99	90 (min)
7 Day		104	90 (min)
28 Day		101	90 (min)
Length Change (% Control		99	120 (max)
Durability Factor		100	80 (min)
Bleeding		85	102 (max)

a These tests performed by Herron Testing Laboratories, Inc.

Table A-4. Analysis of Gulf Coast Portland Cement compliance with ASTM C-150, "Standard Specification for Portland Cement". [a]

Criteria	Cement	ASTM C-150 Specification
Chemical (%)		
SiO_2	21.10	
Al_2O_3	4.98	
Fe_2O_3	3.12	
CaO	63.98	
MgO	1.29	6.0 (max)
SO_3	2.80	3.0 (max)
LOI	2.44	3.0 (max)
Na_2O Equiv	0.38	0.6 (max)
C_3S	54.1	
C_2S	19.8	
C_3A	8.0	
C_4AF	9.5	
Physical		
Autoclave Expansion (%)	0.10	0.80 (max)
No. 325 Sieve (% Retained)	16.3	
Wagner Turbidemeter (cm^2/g)	1820	1600 (min)
Air Permeability (cm^2/g)	3890	2800 (min)
Air Content of Mortar (%)	8.1	12.0 (max)

Table A-4 (Continued)

Criteria	Cement	ASTM C-150 Specification
Gillmore Time of Set (Hr : Min)		
Initial	2 : 35	1 : 00 (min)
Final	4 : 50	10 : 00 (max)
Compressive Strength		
1 Day	1400	
3 Day	3105	1800 (min)
7 Day	4050	2800 (min)

a This test series performed by the Gulf Coast Portland Cement lab.

APPENDIX B

UNPUBLISHED TEST PROCEDURES

No. 200 Sieve Analysis

Materials and Equipment

The materials and equipment necessary to the performance of this test are as follows:

1. Standard No. 200 mesh sieve
2. Scale accurate to $\pm$ 0.5 grams
3. A source of gently flowing water
4. A source of heat to dry the fly ash
5. Small flexible bristled brush to clean retained particles from the sieve
6. Representative sample of fly ash.

Test Procedure

The steps necessary to perform this test are described below:

1. Weigh out 50 $\pm$ 0.5 grams of fly ash and place it on the No. 200 sieve.
2. Run a gently flowing stream of water across the sample accompanied by a slow wrist motion (being careful not to slosh any of the material over the sides of the sieve).
3. When all of the minus 200 sieve particles appear to have washed through, place the sieve where it can dry without being disturbed.
4. After drying, gently, but firmly brush the residue off the sieve and weigh it to determine the percent retained.

This test will not permit the determination of the exact amount of material retained on a No. 325 sieve. The No. 200 sieve analysis is merely intended to serve as an expedient field test for quality control of fineness, and for this purpose it is quite adequate.

Fly Ash CaO Heat Evolution Test

This test involves the isothermic reaction that occurs when hydrochloric acid is added to fly ash. The chemical reaction that occurs is:

$$CaO + 2HCl \rightarrow CaCl + H_2O + \underline{HEAT}$$

There is a linear relationship between the rise in temperature and the total Calcium Oxide present.

Materials and Equipment

The materials and equipment required to perform this test are as follows:

1. U-Shaped Evacuated Thermos Bottle with a stopper that has a hole through the center to accommodate a thermometer
2. 100 ml graduated cylinder
3. Scales accurate to ± 0.2 grams
4. 15 percent hydrochloric acid
5. Two thermometers - one ranging from 0 to 100°C to measure the temperature rise, and the second covering a range that will include the initial temperature of the fly ash

6. A representative fly ash sample.

Figure B-1 is a photograph of the materials and equipment necessary to perform this test.

Procedures

The procedure for determining the total CaO content of an ash by the Heat Evolution method may be summed as follows:

1. Allow the fly ash, acid and thermos bottle to reach an equal and constant temperature and record the temperature (initial temperature).
2. Weigh 20 grams ± 0.2 grams of fly ash and place it in the bottom of the thermos bottle.
3. Add 75 ml of 15 percent HCl to the fly ash within the thermos bottle and stir to insure mixing.
4. Quickly cover the thermos bottle with the stopper and insert the thermometer, being sure the tip of the thermometer is touching the bottom of the bottle.
5. Observe the thermometer until a drop in temperature is seen.
6. Subtract the highest temperature observed from the original temperature found in Step 1. This will give a change in temperature.
7. Read the percentage of CaO content from the appropriate graph (Figure B-2).

Figure B-1. Photograph of CaO heat evolution test materials and equipment.

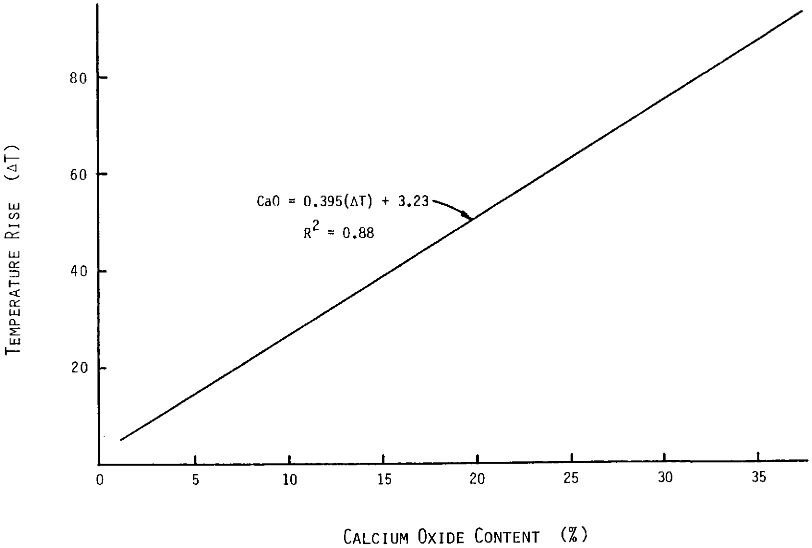

Figure B-2. Calcium content indicated by the CaO Heat Evolution Test.

APPENDIX C

RESULTS OF CHEMICAL OXIDE ANALYSIS AND VARIABILITY TESTING

Table C-1. Results of variability testing for unprocessed fly ash from plant D.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution
1	18.8	9	2.54	22.8
2	21.0	12	2.59	23.2
3	20.2	11	2.54	23.8
4	20.2	11	2.58	24.0
5	22.3	13	2.66	22.7
6	23.4	14	2.58	25.1
7	23.2	14	2.61	24.1
8	22.6	13	2.60	
9	20.2	11	2.60	21.3
10	20.8	11	2.43	20.7
11	17.6	8	2.66	23.0
12	17.5	8	2.49	23.8
13	17.2	8	2.44	23.3
14	15.1	8	2.54	24.8
15	17.0	8	2.52	24.7
16	14.5	7	2.63	22.0
17	13.8	7	2.64	23.7
18	15.6	7	2.60	24.8
19	14.7	6	2.65	23.2
20	15.2	6	2.62	26.0
21	16.9	8	2.60	21.8
22	16.0	8	2.54	22.9
23	16.6	8	2.52	22.0

Table C-1. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
24	16.9	8	2.63	23.3
25	16.9	8	2.55	21.7
26	15.4	8	2.55	21.6
27	14.4	6	2.58	23.0
28	14.7	7	2.58	23.6
29	14.6	7	2.62	22.5
30	15.2	7	2.62	22.5
31	16.8	10	2.56	26.0
32	18.6	8	2.58	27.3
33	15.9	8	2.65	22.1
34	19.5	10	2.52	21.9
35	20.3	9	2.51	22.9
36	19.3	8	2.49	22.3
37	18.4	8	2.54	22.8
38	16.4	8	2.54	23.3
39	20.2	10	2.51	25.3
40	19.3	10	2.53	22.8
41	19.0	8	2.53	24.1
42	19.2	10	2.55	25.1
43	18.2	9	2.58	25.1
44	18.7	8	2.58	25.3
45	18.7	9	2.58	24.1

Table C-1. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
3- 1	14.0	7	2.48	25.4
3- 2	15.1	7	2.53	26.6
3- 3	16.1	9	2.59	26.5
3- 4	15.3	8	2.48	25.5
3- 5	15.2	9	2.57	25.8
3- 6	17.2	8	2.58	26,0
3- 7	16.6	9	2.59	24.9
3- 8	17.0	11	2.58	25.4
3- 9	15.9	8	2.59	26.6
3-10	12.5	6	2.64	27.8
3-11	14.5	8	2.62	26.6
3-12	16.7	10	2.63	26.7
3-13	14.9	8	2.61	25.0
3-14	15.1	8	2.60	26.3
3-15	12.2	6	2.64	28.2
4- 1	17.6	8	2.68	28.5
4- 2	19.3	9	2.59	23.2
4- 3	21.7	10	2.57	23.4
4- 4	19.2	8	2.56	23.3
4- 5	17.8	8	2.59	23.2
4- 6	13.2	5	2.59	25.3
4- 7	15.4	8	2.57	23.4
4- 8	17.4	8	2.54	22.3

Table C-1. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	Ca O by Heat Evolution Test
4- 9	17.2	8	2.55	24.1
4-10	23.4	10	2.53	21.8
4-11	16.9	8	2.58	23.0
4-12	18.9	10	2.56	22.4
4-13	16.9	9	2.55	22.5
4-14	15.8	8	2.59	23.4
4-15	17.0	8	2.50	22.9
4-16	18.0	9	2.60	23.3
5- 1	15.2	11	2.51	26.4
5- 2	12.6	7	2.51	26.4
5- 3	13.2	7	2.48	25.5
6- 3	13.1	6	2.65	27.2
6- 4	14.0	7	2.59	24.82
6- 5	28.8	15	2.63	25.7

Table C-2. Results of chemical oxide analysis of unprocessed fly ash from plant D.

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
6	41.37	24.50	4.82	23.29	3.35	1.12	0.49	0.55
20	41.47	24.49	4.81	23.82	3.31	0.99	0.51	0.14
32	38.78	23.73	5.26	24.87	4.32	1.78	0.73	0.29
39	40.69	25.40	5.14	22.70	3.96	1.12	0.66	0.27
3- 3	40.16	21.70	4.76	24.90	4.81	1.47	0.08	0.32
3- 7	40.92	22.60	4.86	24.30	4.81	1.48	0.12	0.02
3-12	40.00	21.40	4.85	25.70	4.31	1.52	0.05	0.08
3-13	40.14	21.00	4.89	24.30	4.69	1.42	0.13	0.12
4- 1	36.61	21.73	3.96	33.80	1.56	1.29	0.47	0.50
4- 6	42.17	24.76	4.49	23.20	2.07	2.28	0.76	0.34
4-10	38.54	22.20	4.14	29.31	2.67	1.58	0.84	0.42
5- 1	43.80	19.80	4.65	22.50	4.23	1.44	0.25	0.78
5- 2	39.60	23.10	4.98	23.50	4.70	1.42	0.21	0.18
5- 3	40.70	21.50	4.70	23.60	4.70	1.45	0.28	0.36

Table C-2. (Continued).

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
6- 3	38.42	24.70	4.58	25.76	3.06	1.67	0.78	0.88
6- 4	30.56	21.31	7.49	33.24	3.52	2.42	0.32	0.80

Table C-3. Results of variability testing for processed fly ash from plant D.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
50	14.0	6	2.60	25.4
51	13.0	6	2.60	25.5
52	13.7	6	2.62	25.5
53	14.0	6	2.60	24.4
54	23.9	14	2.53	21.3
55	17.0	8	2.53	21.3
56	20.0	10	2.50	21.9
57	13.0	6	2.59	25.4
58	17.3	8	2.53	23.6
59	17.2	10	2.54	23.5
60	17.4	9	2.53	24.5
61	17.9	9	2.53	24.5
62	30.2	16	2.49	19.0
63	18.9	10	2.56	24.9
64	19.5	10	2.58	24.6
65	15.5	7	2.59	25.7
66	25.1	14	2.53	21.2
67	12.5	6	2.59	26.6
68	12.7	6	2.55	26.9
69	13.1	6	2.59	26.9

Table C-4. Results of variability testing for fly ash from plant H.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
1	13.8	6	2.60	28.4
2	13.7	7	2.60	26.5
3	15.2	7	2.56	26.0
4	14.0	7	2.62	29.0
5	14.0	6	2.63	27.6
6	14.0	6	2.60	28.3
7	14.5	7	2.60	26.3
8	14.0	6	2.53	27.6
9	14.9	6	2.56	27.7
12	15.7	8	2.56	25.0
16	18.1	9	2.58	25.4
17	18.1	8	2.59	24.7
18	18.0	9	2.56	25.0
19	16.8	8	2.59	
20	16.9	6	2.59	26.0
23	16.4	8	2.59	27.0
24	15.4	8	2.63	24.7
25	15.3	7	2.60	24.3
26	15.8	7	2.62	26.0
27	15.7	7	2.62	24.3
28	19.0	9	2.62	27.0
29	18.1	9	2.63	28.1
30	16.3	8	2.60	28.0

Table C-4 (Continued).

Sample No.	(% Retained)	(% Retained)	Specific Gravity	CaO by Heat Evolution Test
31	19.0	9	2.66	26.0
32	15.5	8	2.66	25.7
33	13.8	6	2.64	27.2
34	15.4	6	2.64	24.6
35	15.3	6	2.60	27.5
36	12.6	5	2.63	25.9
37	12.4	5	2.59	27.7
38	12.0	5	2.63	27.9
39	22.9	11	2.64	25.9
40	15.3	6	2.62	24.6
41	12.3	5	2.64	24.5
42	15.9	7	2.64	23.6
43	23.2	10	2.60	26.3
44	14.7	7	2.61	28.3
45	16.3	7	2.60	26.7
8-1A	15.0	6	2.66	27.8
8-1B	14.7	6	2.66	27.2
8-1C	16.0	7	2.66	27.8
8-1D	15.3	7	2.63	25.1
8-1E	16.0	7	2.65	27.3
8-2A	14.1	7	2.60	28.8
8-2B	14.4	6	2.65	26.9

Table C-4 (Continued).

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
8-2C	14.9	7	2.62	27.8
8-2D	14.5	7	2.65	28.4
8-2E	17.0	10	2.65	28.0
8-3A	14.6	6	2.65	26.9
8-3B	16.9	10	2.62	25.7

Table C-5. Results of chemical oxide analysis of fly ash from plant H.

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
1	32.43	23.32	5.72	29.39	4.52	2.76	1.20	0.42
9	36.09	23.86	6.20	26.40	3.95	2.27	0.85	0.26
17	36.95	22.85	6.77	25.76	4.06	2.06	0.79	0.36
19	37.00	22.79	6.55	25.96	4.13	2.22	0.78	0.36
8-1B	34.58	20.00	7.22	28.00	5.10	2.30	0.51	0.46
8-2A	34.50	21.50	6.03	28.10	5.00	2.32	0.50	0.46
8-3A	34.62	19.10	6.41	29.00	5.10	2.34	0.49	0.48

Table C-6. Results of variability testing for fly ash from plant M.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution
1	33.2	17	2.26	8.4
2	33.0	14	2.28	9.3
4	28.8	14	2.28	9.4
5	28.7	13	2.25	9.7
7	29.0	13	2.23	
14	26.0	12	2.30	9.6
15	25.6	12	2.26	9.3
17	27.6	13	2.24	10.0
18	28.4	13	2.31	9.5
19	28.1	13	2.28	9.5
20	29.2	14	2.22	9.8
21	29.9	13	2.31	9.4
22	33.8	16	2.26	9.1
23	29.2	14	2.26	10.0
24	30.3	14	2.21	9.5
25	30.6	14	2.21	9.7
26	27.0	12	2.29	10.9
27	30.6	14	2.29	10.0
28	25.8	12	2.30	9.6
29	33.6	16	2.26	8.3
30	29.8	13	2.34	9.7
31	29.5	14	2.29	10.0
32	28.3	14	2.26	9.2

Table C-6. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 325 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution
33	26.2	12	2.30	10.8
34	40.1	18	2.21	8.7
35	29.9	14	2.25	9.9
36	19.7	9	2.27	10.7
37	25.7	14	2.33	10.3
38	29.7	15	2.25	9.2
39	33.6	16	2.23	9.0
43	34.7	16	2.20	8.6
46	31.7	15	2.24	9.7
48	24.9	12	2.26	9.5
49	31.6	15	2.29	9.2
51	27.3	12	2.31	10.1
52	34.9	16	2.24	9.6
55	29.0	14	2.26	10.0
56	30.1	15	2.29	9.8
58	28.7	16	2.31	10.3
61	29.8	14	2.30	9.5
62	29.7	14	2.21	9.9
65	28.4	14	2.25	10.0
67	31.8	14	2.23	9.5
78	29.0	15	2.25	
1- 1	28.7	13	2.29	9.5
1- 2	31.6	12	2.29	10.9

Table C-6. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
1- 3	10.7	4	2.33	9.5
1- 4	24.6	5	2.30	9.4
1- 5	33.0	14	2.28	9.2
1- 6	19.6	8	2.35	11.6
1- 7	26.0	12	2.32	12.1
1- 8	20.1	9	2.34	11.0
1- 9	29.5	15	2.33	9.1
1-11	33.6	16	2.29	8.4
1-12	20.2	6	2.37	11.5
1-13	25.6	12	2.39	18.7
1-14	31.7	15	2.27	8.0
1-15	29.0	13	2.28	8.0
1-16	27.6	13	2.22	15.8
1-17	28.8	14	2.19	12.1
1-18	28.4	14	2.20	9.3
1-19	33.9	16	2.27	8.8
1-20	29.2	14	2.25	9.2
1-21	40.1	18	2.23	8.0
1-22	33.8	16	2.26	8.2
1-23	29.2	15	2.26	8.7
1-24	42.3	20	2.26	8.0
1-25	39.6	20	2.25	8.0
1-26	37.4	18	2.27	8.4

Table C-6. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
1-27	33.2	17	2.26	8.0
1-28	38.3	18	2.25	8.6
1-30	30.6	14	2.28	9.5
1-31	27.0	12	2.28	9.0
1-32	15.5	6	2.32	11.9

Table C-7. Results of chemical oxide analysis of fly ash from plant M.

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
29	60.13	25.47	3.29	8.73	2.10	0.18	0.02	0.11
30	60.65	24.77	3.47	8.91	2.06	0.05	0.03	0.07
34	60.32	25.65	3.33	8.40	1.99	0.14	0.03	0.14
52	60.28	25.34	3.34	8.77	2.08	0.05	0.03	0.04
1- 3	62.58	20.40	3.43	9.00	2.17	0.42	0.03	0-04
1- 8	61.56	18.90	3.41	12.00	2.27	0.52	0.05	0.12
1-13	55.90	16.10	3.06	21.30	1.97	0.86	0.10	0.04
1-24	63.70	21.40	3.17	7.30	2.16	0.30	0.03	0.08

Table C-8. Results of variability testing for fly ash from plant W.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained	Specific Gravity	CaO By Heat Evolution
1	10.5	5	2.55	27.5
2	18.0	8	2.63	28.4
3	19.0	11	2.67	27.0
4	21.4	11	2.65	27.3
5	19.9	10	2.65	28.2
6	9.8	4	2.59	28.5
7	7.9	4	2.57	28.2
8	9.2	4	2.60	28.6
9	9.3	3	2.60	29.5
10	8.7	4	2.59	27.9
11	8.4	4	2.59	28.5
12	9.5	5	2.61	28.3
13	9.2	4	2.60	27.9
14	9.5	4	2.60	28.5
15	10.1	4	2.61	28.5
16	10.7	5	2.56	28.6
17	17.8	8	2.61	26.6
18	17.4	8	2.57	26.6
19	17.0	8	2.57	27.4
20	14.2	6	2.59	28.1
21	16.6	7	2.53	28.0
22	17.3	8	2,57	27.7
23	18.5	9	2.59	27.8

Table C-8 (Continued).

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
24	18.7	10	2.56	27.0
25	17.1	8	2.56	27.5
26	16.6	8	2.57	28.0
27	16.2	8	2.67	26.2
28	19.5	10	2.56	27.5
29	19.6	9	2.63	28.6
30	19.4	9	2.56	27.7
31	18.6	9	2.53	28.2
32	20.8	10	2.55	27.5
33	17.5	9	2.61	28.1
34	17.6	8	2.60	28.3
35	18.9	10	2.57	28.4
36	17.9	9	2.61	28.6
37	17.5	9	2.63	28.1
38	19.9	10	2.60	28.4
39	19.1	10	2.57	28.3
40	17.7	9	2.65	29.2
41	17.6	9	2.63	28.1
42	18.9	10	2.63	28.9
43	17.2	9	2.63	28.5
44	18.3	9	2.63	28.6
45	18.0	9	2.63	

Table C-8. (Continued).

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
2- 1	15.0	8	2.70	31.2
2- 2	17.5	8	2.70	30.0
2- 3	17.0	8	2.70	29.8
2- 4	13.7	6	2.66	27.8
2- 5	14.2	6	2.67	28.9
2- 6	16.2	8	2.70	30.0
2- 7	17.0	8	2.70	29.4
2- 8	16.5	8	2.70	28.9
2- 9	17.3	9	2.69	28.0
2-10	16.9	9	2.69	27.6
2-11	15.5	8	2.69	29.0
2-12	18.0	9	2.69	28.2
2-13	17.9	10	2.70	28.0
2-14	15.6	9	2.68	30.0
2-15	16.2	8	2.70	28.6
2-16	16.5	8	2.70	30.6
2-17	9.2	4	2.70	27.6
2-18	8.4	4	2.69	29.0
2-19	8.4	3	2.68	28.8
2-20	16.8	8	2.69	28.0
2-21	15.6	6	2.70	29.2
2 22	14.0	6	2.70	30.8

Table C-8. (Continued).

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
2-23	14.0	5	2.67	28.2
2.24	15.2	6	2.69	28.8

Table C-9. Results of chemical oxide analysis of fly ash from plant W.

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
7	34.02	24.81	5.35	27.51	4.27	2.68	1.21	0.34
9	33.87	24.14	5.41	28.00	4.27	2.80	1.10	0.34
31	36.11	23.91	5.64	26.25	4.03	2.47	0.84	0.41
44	34.39	23.30	5.71	27.19	4.29	3.15	1.14	0.41
2- 1	31.87	20.90	5.71	33.00	3.44	4.07	1.35	0.30
2- 4	33.63	21.44	5.48	31.13	3.20	3.23	1.28	0.40
2 12	33.42	21.31	5.59	30.93	3.44	3.21	1.26	0.60

Table C-10. Results of variability testing for fly ash from plant B.

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO By Heat Evolution
2	16.6	6	2.59	18.7
3	16.0	6	2.60	18.4
6	16.9	7	2.60	19.3
7	15.8	6	2.62	18.5
8	18.2	6	2.52	16.1
9	17.4	7	2.51	15.6
10	17.9	7	2.54	15.3
11	17.8	8	2.54	15.1
15	17.9	8	2.54	18.4
18	17.6	7	2.54	18.8
21	18.3	8	2,58	18.0
22	18.4	7	2.54	16.8
23	18.3	6	2.56	17.4
26	14.2	5	2.55	18.0
27	13.2	5	2.56	19.0
28	11.7	5	2.56	19.2
29	13.6	6	2.56	18.7
30	10.2	5	2.57	19.6
31	13.1	5	2.59	20.4
32	12.9	6	2.60	19.3
33	16.7	7	2.55	17.8
34	16.0	7	2.54	16.7
35	13.0	6	2.58	20.5

Table C-10. (Continued)

Sample No.	No. 325 Sieve (% Retained)	No. 200 Sieve (% Retained)	Specific Gravity	CaO by Heat Evolution Test
36	17.9	8	2.53	16.7
37	16.1	7	2.54	17.4
38	15.8	7	2.54	17.7
39	16.6	8	2.60	17.2
40	18.5	8	2.51	16.8
41	18.2	8	2.54	17.8
42	18.9	8	2.53	18.5
43	19.2	8	2.50	18.9
44	13.6	6	2.56	20.4
45	10.6	4	2.60	21.2
46	14.4	6	2.53	17.4
47	14.9	6	2.52	18.0
48	13.1	5	2.54	19.2
49	19.1	8	2.51	19.0
50	14.7	7	2.53	17.3
51	16.8	7	2.53	17.7
52	15.4	6	2.55	19.9
53	15.4	6	2.55	18.6
54	14.3	6	2.54	17.0
55	14.9	6	2.54	17.0
56	13.7	6	2.54	17.0
57	15.1	6	2.55	16.7
11-1	16.0	7	2.53	18.2
11-2	15.4	8	2.53	16.3

Table C-11. Results of chemical oxide analysis of fly ash from plant B.

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Equiv. Na_2O	LOI
2	48.98	17.40	7.58	18.50	3.56	1.38	0.18	0.34
7	49.26	16.80	7.66	18.60	3.53	1.48	0.16	0.50
15	49.96	17.40	6.92	18.00	3.23	1.45	0.20	0.52
28	49.56	17.60	7.26	17.90	3.53	1.45	0.19	0.28
11-1	51.64	16.80	7.06	17.80	3.47	1.47	0.23	0.44
11-2	52.04	16.40	7.05	17.10	3.40	1.41	0.23	0.50

VITA

William Carlton McKerall was born on April 5, 1957, in Waco, Texas, the son of Charles and Jeannine McKerall. At an early age he moved with his family to New Braunfels where he remained until he graduated from New Braunfels High School in May of 1975. He received a Naval ROTC scholarship to Texas A&M University and began classes there in September of 1975, studying Civil Engineering. In August of 1979, he received a Bachelor of Science degree in Civil Engineering, specializing in Construction Management. Directly pursuant to his undergraduate degree, he enrolled in the graduate college at Texas A&M University, and began working toward a Master of Science in Civil Engineering. In August of 1980, he was commissioned an Ensign in the United States Navy, Civil Engineer Corp to be stationed at Williamsburg, Virginia.

The author's permanent address is: P. O. Box 417, New Braunfels, Texas 78130.

The typist for this thesis was Mrs. Beatrice Cullen.